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OPERATION GREENHOUSE

SCIENTIFIC DIRECTOR'S REPORT

VOLUME II

PART II—EVALUATION OF PROGRAM 2

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Volume II

Part II

Evaluation of Program 2

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THE SCIENTIFIC DIRECTOR'S REPORT

Part II

EVALUATION OF PROGRAM 2

Approved by: ALVIN C. GRAVES
Scientific Director

The University of Chicago
Chicago, Illinois

Los Alamos Scientific Laboratory
Los Alamos, New Mexico

December 1951

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Preface

The approval of a biomedical program for the Nuclear Weapons Tests at Eniwetok in 1951, represented a favorable change in the policy of the Division of Military Applications, U. S. Atomic Energy Commission. With the exception of the qualitative clinical studies conducted as a part of Operation Crossroads at Bikini in 1946, there have been no biological experiments in connection with tests of atomic weapons. In spite of the fact that a nuclear weapon is capable of inflicting injuries of an entirely novel type, medical scientists have had little opportunity to study the new disease, whole-body radiation injury, and the new forms of trauma, such as the flash burns and the air-blast injury which are caused by the detonation of an atomic bomb. Including Operation Greenhouse, there have been but three occasions when living subjects exposed to an atomic explosion could be examined. In Japan, the allied conditions were appalling. The majority of the patients suffered multiple injuries, and these injuries were complicated by epidemic disease, malnutrition, and exhaustion. The Japanese physicians who cared for the casualties were too busy attempting to provide even minimal medical care to have time for careful observation. The American scientists were not able to study the patients until the 3rd or 4th week after the bombing. At Bikini, the biological studies were designed to yield only qualitative information. The uncertainty of the air drop, the shifting position of ships at anchor, and the occurrence of multiple injuries in the subjects, complicated by exposure, all combined to yield clinical data that were difficult to interpret. It is not surprising that the first two studies of the medical sequelae of the detonation of an atomic bomb raised more questions than were answered. Actually, these studies to a large extent served only to verify certain broad assumptions based on experience with X rays. None of the data, however, could be described as definitive. The situation at Operation Greenhouse was much more favorable. With weapons, the yield of which was fairly certain, detonated on a tower, it was feasible to plan quantitative studies of individual effects, as well as clinical studies under well-controlled conditions. The long period of preparation made it possible to conduct the necessary control studies and to use healthy animals that were thoroughly acclimatized to the tropical environment. Since all the specimens were recovered within a few hours of the detonation, serious complications resulting from exposure, starvation, and dehydration were avoided. In general, the experimentation of Program 2 was successfully executed, and results were obtained which should have a profound influence on future investigations of the medical and biological effects of nuclear weapons.

The immediate contribution to the planning of effective medical care for the victims of atomic warfare is not so spectacular as may have been expected. It would be unusual, to say the least, if the first careful study of any new disease provided the definitive information that was required for its control. In the history of medical science few diseases have yielded to the first examination, and the injury inflicted by an atomic bomb is no exception. It is characteristic of the medical sciences to employ the empirical approach to the causation and treatment of disease. There is an urgency associated with disease and suffering which does not encourage the search for fundamentals. The prevailing attitude has always been first to discover practical means to alleviate suffering and hasten recovery, and then to investigate the details of pathogenesis and the mechanism of recovery. The planning of the biomedical program was typical of medical science in general in this

respect, and the information sought and obtained was primarily empirical. Certain of the fundamental problems of radiobiology were explored, *e.g.*, relative biological efficiency of nuclear radiation compared to high-voltage X rays. The intent was to study methods for future research rather than to seek an early solution.

This volume contains an evaluation of the biomedical program of Operation Greenhouse. The first section describes in some detail the planning and preparations for the field tests. The principal objectives are discussed briefly, and the theoretical basis for the design of the various experiments is presented. Medical and biological research under field conditions confronts the investigator with many problems which do not occur in the laboratory or in the wards of a hospital. Since further biomedical studies are necessary and will be done, it seemed proper to describe some of these problems and some of the solutions that were devised. The second section contains an evaluation of the experimental data obtained at Eniwetok. The evaluation is presented on several levels: with respect to the adequacy of the experimentation, with respect to the reliability of the data, and with respect to the application of the data to medical disaster planning and to the planning of future investigations. The biomedical program consisted of 20 projects which were mutually complementary and interdependent to a remarkable extent. The final reports of the individual projects, and of the special control studies that were necessary, are contained in the annexes to the Scientific Director's Report. The over-all picture of the experimentation and the broad interpretation of the results are to be found in this volume.

GEORGE V. LEROY

Acknowledgments

The Director of the biomedical program is confronted with an almost hopeless task when he attempts to acknowledge adequately the help of the ad hoc committee and the scientific personnel of Task Unit 3.1.2 which he received from the time of the first meeting of the ad hoc committee in June 1949, until the manuscript of this report was submitted to the printer. The success of the program is a well-deserved credit to their wisdom and judgment. It was a privilege to serve with both groups, and it is impossible to thank them adequately for their contributions.

The Scientific Director, Alvin C. Graves, was a constant source of inspiration and supported the program unfailingly through a series of vicissitudes and exasperations too numerous to relate. His colleagues in J-Division of the Los Alamos Scientific Laboratory displayed remarkable patience at all times, and were most helpful in providing the physical data that were needed for planning equipment and the design of the experiments.

The Commanding Officer of the Naval Medical Research Institute, RADM Charles F. Behrens, MC, USN, and later CAPT Wilbur E. Kellem, MC, USN, never failed to support any request that was submitted to them. More than any other agency, this fine laboratory and its staff were responsible for the successful execution of the biomedical program. During the period 1949 to 1951, almost the entire effort of the Atomic Defense Division of the Institute, and of the Bureau of Medicine and Surgery, was directed to Operation Greenhouse.

The individual scientists who attended conferences and served as personal advisors to the Director are too numerous to mention. He is deeply indebted to them and acknowledges their generous assistance with gratitude. As they read this report they will recognize their contributions, and will surely consider the successful experiment a just reward for their efforts.

The material presented in this volume is the result of the efforts of all the personnel of Program 2, and of their consultants. The interpretations offered are not those of the author alone, but have been derived from numerous conferences and discussions. The responsibility for the conclusions, however, belongs to the author who believes that he has recorded faithfully the views of his colleagues. Among all those who have assisted in the planning and execution of the biomedical program, and in the preparation of the report, the greatest contribution was made by Wright H. Langham, the deputy director of the program. The task could not have been completed without his help and wise counsel.

GEORGE V. LEROY

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Section 1

EXPERIMENTATION

by
George V. LeRoy
of
The University of Chicago

Abstract

The biomedical program of the 1951 tests of nuclear weapons at Eniwetok is described in some detail. The purpose of the experimentation was to obtain information that could be used in planning adequate medical care for victims of atomic warfare. To accomplish this purpose experiments were designed: (a) to measure biologically the dose of gamma radiation and neutrons as functions of distance; (b) to determine the relative biological efficiency of gamma radiation; (c) to determine the median lethal dose of gamma radiation for large animals; (d) to specify the quality of the gamma ray; (e) to define the characteristics of flash burns; (f) to estimate the nature of the radiation hazard to personnel in aircraft traversing an atomic cloud; and (g) to examine the protection afforded by a foxhole. The predicted values for the field variables (nuclear radiation, thermal radiation, and blast) are discussed summarily, and the design of the experiments is described. For the benefit of those who may plan other biomedical tests, a synopsis of the procedures employed is presented with critical comments.

Chapter 1

Introduction

1.1 HISTORY OF PROGRAM 2

1.1.1 The Ad Hoc Committee

The preliminary plans for the 1951 weapons tests included an acceptable biomedical program. Proposals for participation in this program were solicited from interested agencies of the National Military Establishment and the U. S. Atomic Energy Commission. At the request of Alvin C. Graves, the Scientific Director of the tests, Shields Warren of the Division of Biology and Medicine, AEC, appointed an ad hoc committee to examine the proposals submitted and to prepare a protocol for observations in the field of biology and medicine, which it was desirable to make in the 1951 test. This committee met in Washington, D. C., 7 to 9 June 1949, to review the 45 proposals that had been received. The protocol for a biomedical program, which was submitted as the report of the committee, defined objectives, limited the scope of the experimentation, approved 25 of the proposed projects, and submitted recommendations for the minimum requirement for laboratory facilities to implement the program. Subsequent changes in the program were few in number and did not violate the objectives and restrictions of the ad hoc committee.

1.1.2 The Approved Program

In July 1949, the chairman of the ad hoc committee submitted the protocol to the J–7 committee, Frederick Reines, Chairman, whose function was to review all experimental proposals for the 1951 tests with regard to their feasibility as a part of a weapons test. As a result of this review the number of approved projects was reduced to 18, and the program was strengthened by the integration of the biomedical plan with the plan for physical measurements of Program 1. The program as approved by the J–7 committee was then approved by J-Division; by the Joint Proof Test Committee, Lt. Gen. E. R. Quesada, USAF, Chairman; and by the Medical Advisory Committee of the AEC, Alan A. Gregg, Chairman. These actions were accomplished during July 1949, and at about the same time, George V. LeRoy was designated Director of Program 2, the biomedical program, by Alvin C. Graves. The Joint Panel on Medical Aspects of Atomic Warfare of the Research and Development Board reviewed the biomedical program at its second meeting, 7 October 1949, and endorsed it in principle. At its third meeting, 16 to 17 December 1949, the panel approved the program and this approval was endorsed later by the Committee on Medical Sciences of the Research and Development Board, Francis Blake, Chairman. The final version of the program is set forth in the schedule of experiments, Tables 1.1 through 1.4.

1.1.3 Implementation

The fiscal policy of the biomedical program was developed in a series of conferences with representatives of the Joint Proof Test Committee, the Division of Military Applications, AEC; and the Atomic Defense Division, Bureau of Medicine and Surgery, Department of the Navy. The broad features of this policy which had a beneficial effect on subsequent planning were as follows:

(a) Costs of construction of facilities on Japtan Island were charged to weapons-test funds at the disposal of the Scientific Director, Alvin C. Graves.

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(b) Costs of equipment, supplies, operating expenses, and station installations on the "shot" islands were charged to a Naval Working Fund held by the National Naval Medical Center. The money for this fund was transferred from the Air Force Management Fund held by Joint Task Force Three after the program was approved by the Research and Development Board.

(c) Costs of control studies, the development of special apparatus, and pretest expenses were borne by the various agencies concerned to the extent permitted by their respective budgets.

(d) Since the biomedical program consisted of 18 complementary and interdependent projects, an administrative section was organized at the Naval Medical Research Institute which handled all the fiscal and administrative affairs of Program 2, and later of Task Unit 3.1.2. During the period prior to the assignment of funds from Joint Task Force Three, the necessary costs of implementation were assumed by the Naval Medical Research Institute.

The first phase of Program 2 consisted of the establishment of the animal colony on Japtan Island, Eniwetok Atoll. At the direction of the Chief, Bureau of Medicine and Surgery, Department of the Navy, Bumed Unit One was organized with an authorized strength of 1 officer (the officer-in-charge) and 50 enlisted men. This unit was placed under the administrative control of the Naval Medical Research Institute, and in 1951, operational control was assumed by the Commander, Task Unit 3.1.2. Prior to this time, the Director of Program 2 exercised functional control on an informal basis which was entirely satisfactory to all concerned. An advance party of Bumed Unit One led by CAPT R. H. Draeger, MC, USN, a Deputy Director of Program 2, arrived at Eniwetok in November 1949, and established the mouse breeding colony. The breeding stock of swine and dogs, accompanied by a qualified veterinarian, arrived on Japtan in July 1950, at which time the unit was increased to its authorized strength.

The detailed planning of the various projects was facilitated by a series of conferences attended by project personnel and consultants in special fields of biology and medicine. Concurrently with this, control studies were carried out, and special apparatus and equipment were procured and transported to Japtan.

The final phase began in January when the scientific personnel began to assemble on Japtan. At this time the administrative and planning entity which had been Program 2, became the operational entity, Task Unit 3.1.2. At the time of the tests the strength of the Task Unit was 100, of which 41 were scientists, 58 were the personnel of Bumed Unit One, and one served as an administrative rear echelon in the United States.

TABLE 1.1 SCHEDULE OF BIOMEDICAL EXPERIMENTS FOR DOG SHOT

PROJECT NO.	STATION NO.[a]	BRIEF DESCRIPTION OF EXPERIMENT	MATERIAL EXPOSED	PROJECT OFFICER
		On Site C		
2.5.5.1	73, 74	Gamma Radiation and Neutrons as a Function of Distance	*Tradescantia*	A. D. Conger
2.5.5.4	74	Dose of Gamma Radiation as a Function of Distance	Mice	R. E. Carter
2.5.5.5	73	Neutrons as a Function of Distance	Mice	R. E. Carter
		In Drone Aircraft		
2.5.4	3 B–17's	a) Integrated Dose of Gamma Radiation during Cloud Pass b) Distribution of Fission Products Inhaled during Cloud Pass	Mice	R. E. Carter
2.5.5.1	3 B–17's	Integrated Dose of Gamma Radiation during Cloud Pass	*Tradescantia*	A. D. Conger

[a] Refers to station numbers in instrument location chart and throughout the text of this report and the annexes.

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TABLE 1.2 SCHEDULE OF BIOMEDICAL EXPERIMENTS FOR EASY SHOT

PROJECT NO.	STATION NO.	BRIEF DESCRIPTION OF EXPERIMENT	MATERIAL EXPOSED	PROJECT OFFICER
		On Site E		
2.4.1.1	70, 71	Mortality Rate as a Function of Distance	Mice	E. P. Cronkite
2.4.1.4	72	Mortality Rate as a Function of Distance	Swine	J. L. Tullis
2.4.1.5	72	Mortality Rate as a Function of Distance	Dogs	A. W. Eaton, Jr.
2.4.1.2	83	Sequence of Pathological Changes; Bacteriology	Swine	J. L. Tullis
2.4.1.3	83	Sequence of Pathological Changes; Bacteriology	Dogs	A. W. Eaton, Jr.
2.4.2	75	Thermal-injury Study	Swine and Dogs	H. E. Pearse
2.4.3	83	Sequence of Hematological Changes	Dogs	E. P. Cronkite
2.4.3	83	Sequence of Biochemical Changes	Dogs	R. L. Libby
2.4.4	80, 81, 72 70, 71, 74	Depth Dose as a Function of Distance	Phantoms	F. W. Chambers, Jr.
2.5.1.1	70, 71	Longevity, Carcinogenesis and Induction of Cataracts in Survivors	Mice	J. Furth
2.5.1.2	85	Induction of Cataract by Neutrons	Mice	J. Furth
2.5.5.1	70, 71, 73 85, 511–516	Gamma Radiation and Neutrons as a Function of Distance	*Tradescantia*	A. D. Conger
2.5.5.3	84	Yield of Mutations after Nuclear Radiation	Corn and *Glomerella*	G. W. Beadle
2.5.6				
2.5.5.4	74	Dose of Gamma Radiation as a Function of Distance	Mice	R. E. Carter
2.5.5.5	73	Neutrons as a Function of Distance	Mice	R. E. Carter
		On Site S		
2.4.2	76	Thermal-injury Study	Swine and Dogs	H. E. Pearse
2.4.4	80e	Depth Dose as a Function of Distance	Phantoms	F. W. Chambers, Jr.
2.5.5.1	517, 518, 519	Gamma Radiation as a Function of Distance	*Tradescantia*	A. D. Conger
		On Site T		
2.4.2	77, 78, 78a	Thermal-injury Study	Swine and Dogs	H. E. Pearse
		On Site P		
2.4.2	79	Thermal-injury Study	Swine and Dogs	H. E. Pearse
		In Drone Aircraft		
2.5.4	3 B–17's	(a) Integrated Dose of Gamma Radiation during Cloud Pass (b) Distribution of FP Inhaled during Cloud Pass	Mice	R. E. Carter
2.5.5.1	3 B–17's	Integrated Dose of Gamma Radiation during Cloud Pass	*Tradescantia*	A. D. Conger

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TABLE 1.3 SCHEDULE OF BIOMEDICAL EXPERIMENTS FOR GEORGE SHOT

PROJECT NO.	STATION NO.	BRIEF DESCRIPTION OF EXPERIMENT	MATERIAL EXPOSED	PROJECT OFFICER
		On Site D		
2.3	70	Function of Cylinder Containers	Instruments	R. H. Draeger
2.4.4	80	Depth Dose as a Function of Distance	Phantoms	F. W. Chambers, Jr.
2.5.1.2	85	Induction of Cataracts by Neutrons	Mice	J. Furth
2.5.5.1	73, 74, 85	Gamma Radiation and Neutrons as a Function of Distance	*Tradescantia*	A. D. Conger
2.5.5.4	74	Dose of Gamma Radiation as a Function of Distance	Mice	R. E. Carter
2.5.5.5	73	Neutrons as a Function of Distance	Mice	R. E. Carter
		On Sites R and P, Respectively		
2.4.2	75, 76	Thermal-injury Study	Swine	H. E. Pearse
		In Drone Aircraft		
2.5.4	3 B–17's	(a) Integrated Dose of Gamma Radiation during Cloud Pass (b) Distribution of Fission Products Inhaled during Cloud Pass	Mice	R. E. Carter
2.5.5.1	3 B–17's	Integrated Dose of Gamma Radiation during Cloud Pass	*Tradescantia*	A. D. Conger

TABLE 1.4 SCHEDULE OF BIOMEDICAL EXPERIMENTS FOR ITEM SHOT

PROJECT NO.	STATION NO.	BRIEF DESCRIPTION OF EXPERIMENT	MATERIAL EXPOSED	PROJECT OFFICER
		On Site E		
2.4.5	86	Blast Effects in Foxholes	Dogs	J. C. Talbot
		Common to Program		
2.2		Production of Animals		R. J. Veenstra
2.3		Design of Exposure Equipment		R. H. Draeger

1.2 PURPOSE OF THE BIOMEDICAL EXPERIMENTATION

1.2.1 Introduction

The fundamental objective of the biomedical program was to obtain information which could be of value in planning adequate medical care for victims of atomic warfare and industrial accidents in nuclear energy plants. Since it was not possible to use human subjects for direct experimentation, it was necessary to plan studies using suitable animals, the results of which could be applied to the new problems of military medicine and civil defense created by the use of nuclear weapons. The most important of these problems can be stated in general terms as follows: (1) the prediction of the expected casualty rate due to radiation injury, (2) the nature of radiation injury, (3) the mass treatment of radiation injury and flash burns, and (4) protection for personnel. Previous observations of the effects of an atomic explosion on biological material (see Chap. 2) provide some clues to the solution of these problems. Intensive laboratory studies of the biological effects of ionizing radiation and of thermal burns have been carried out during the past decade. In spite of all these, there are large gaps in our knowledge which hamper the investigators and frustrate the practicing physicians who have the

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responsibility for planning the care of victims of atomic warfare. It was obviously impossible to design a field experiment which could provide definitive solutions to all the problems. It seemed possible that considerable progress could be made toward their solution in the laboratory, and on theoretical grounds, if certain data were made available which could be obtained only by a field study using a nuclear weapon. The specific objectives of the field tests and the reasons for attaching significance to them follow.

1.2.2 Determination of the Relative Biological Efficiency of Initial Nuclear Radiation

The concept of relative biological efficiency (RBE) is important in radiobiology. It is well recognized that equal amounts of ionizing radiations of different wave lengths, expressed as roentgens measured in air, will not have necessarily identical biological effects. The differences that occur are related to such factors as the composition and quality of the radiation (*i.e.*, its wave length and spectrum); the dose rate; the ionization densities; the composition of the tissue irradiated, etc. The means by which a given dose of ionizing radiation is lethal to an animal, or even to a single cell, is not known at the present time. In the case of complex organisms, such as mammals, it appears that lethality is not a single, simple function, but is cumulative, and may occur in several fashions. An obvious goal of radiobiological research is the determination of the means by which ionizing radiation causes death. When the method (or methods) of lethal action is understood, it should be possible to develop protective, antidotal, or therapeutic agents. The most direct approach to the problem can be made if the research worker has at his disposal a source of ionizing radiation, the biological effectiveness of which is identical with, or comparable to that of, the initial nuclear radiation of an atomic bomb. The determination of RBE is essentially a biological assay of the potency of two or more types of ionizing radiation with respect to their capacity to cause a given biological effect. The primary, or reference, measurement of the dose of radiation in roentgens is necessarily made by physical means. In Operation Greenhouse, three systems of biological assay, or biological dosimetry were employed:

1. The *Tradescantia* system depended on the production of chromosomal aberrations in the microspores of *Tradescantia* which were scored 1 day and 4 days after irradiation. The reference sources of irradiation were X rays produced at 250 KVP, gamma rays from cobalt^{60}, and fast neutrons from the Oak Ridge pile.

2. The mouse thymus-spleen system depended upon the decrease in weight of the thymus and the spleen of the LAf_1 mouse, which occurred as a function of dose, and was measured on the 5th day after irradiation. The reference sources of irradiation were X rays produced at 230 KVP.

3. The mouse median-lethal-dose (MLD) system depended on the determination of the MLD for the LAf_1 mouse. The reference sources of irradiation were X rays produced at 250 and 2,000 KVP.

Each of these three biological responses has been studied so extensively in the laboratory that it is appropriate to consider the species in which they occur as calibrated species. In the system of *Tradescantia,* one is concerned only with visible damage to chromosomes of germ cells. In the mouse thymus-spleen system, the response under investigation represents the death of a fraction of the cells (probably the lymphocytes) of which the two organs are composed. With the mouse MLD system, the quantal response of the members of a homogeneous population are studied. The standard error of the estimate of dose using any of these systems is of the order of 15 per cent, or less. The estimation of the RBE depends ultimately upon the physical measurements made in the field by Program 1, and in the laboratory for the reference sources of radiation. The calibrated film packs which were used to measure integrated gamma-ray dose as a function of distance in poor geometry, and neutron foils, were placed inside each of the units that contained the biological dosimeters. By means of intercalibration of the various

physical dosimeters, it is hoped that the standard error of estimate will be comparable to that of the biological dosimeters.

In addition to the three systems of biological dosimetry that were used in what may be called the range of medical interest, two other systems were employed in the high-dose range. The mould *Glomerella* and corn seed were exposed close to zero in an attempt to measure the mixed radiation. With calibrated sources the response of these materials is quite consistent, and they are sufficiently radioresistant to permit their exposure to tens of thousands of roentgens.

1.2.3 Mortality Rate as a Function of Distance

The dosage of delayed gamma radiation at distances not too large is a function of the yield of a nuclear weapon. Since yield can be estimated by a variety of methods, and since the scaling law is simple, it becomes possible to predict the integrated gamma-ray dose which will be received in the absence of any shielding by individuals at various distances from zero. After an attack using nuclear weapons it would be desirable to have a reliable estimate of the number of casualties with radiation injury requiring treatment. Such an estimate can be made if the following information is available in addition to the probable yield: (1) The MLD for man, and (2) the amount of shielding afforded to the various areas by the geometry of the attack, terrain features, buildings, etc. There have been no direct experiments on which to base a value for the MLD of man. The hypothetical value, 400 r, has been widely accepted, and is quoted in many official publications.[1] In Japan, a determined effort was made to establish a reliable value for the MLD in terms of distance from zero. In both Hiroshima and Nagasaki it appeared that the LD_{50} was delivered at approximately 1,250 yd, and at this distance in the open, the dose of gamma radiation should have been approximately 800 r. Because of the geometry of the attack, it is not possible to estimate the reduction of the dose at 1,250 yd as a result of the shielding effect of buildings. It would not be proper to expect this same dose-distance relationship to be obtained in the case of the atomic bombing of troops in the open, or in the case of a surface burst in a city with principally brick and masonry buildings. The uncertainties that exist at the present time will not be reduced by the availability of reliable personnel dosimeters, since it is not possible to interpret the readings in terms of the probable severity of the radiation injury caused by a given whole-body dose.

The extrapolation from animals to man is not entirely satisfactory. The range of values for the LD_{50} of a number of species is given in Table 1.5. Experimental data such as these demonstrate the varying radiosensitivity of species, and also show that the quality of the radiation may have an important influence on the MLD.

TABLE 1.5 THE MEDIAN LETHAL DOSE OF WHOLE-BODY RADIATION

SPECIES	MLD (r)
Mouse, CF1	600
Mouse, LAf_1	750
Guinea Pig, inbred	250
Rat	550
Dog, 250 KVP, rotational	250
Rabbit	800
Dog, 1,000 KVP, bilateral	310
Pig, 2,000 KVP, unilateral	525
Pig, 2,000 KVP, bilateral	425

Since no good data were available on the mortality rate of any species as a function of the dose of gamma radiation from an atomic bomb, three such experiments were planned for Operation Greenhouse. The determination of the LD_{50} of the LAf_1 mice could be used to examine the RBE of the gamma radiation, and to evaluate the influence of intensity on the biological effect. It was believed that the LD_{50} of swine and dogs could be considered as a first approximation of the probable LD_{50} for man. In the absence of any evidence to the contrary, it was not improper

[1] The Effects of Atomic Weapons (Los Alamos Scientific Laboratory and U. S. Government Printing Office, Washington, D. C., 1950).

to assume that man, dog, and swine should display comparable radiosensitivity. Since dose of gamma radiation was to be measured accurately at Greenhouse in the cylinders where the animals were exposed, the geometry of the situation was not important. Although the problem of extrapolation to man still remained, measurement of the dose-mortality response of two large mammals should provide new and important information for planning the medical care of victims of atomic warfare.

1.2.4 Depth-dose Measurement

An important consideration in any study of the biological effects of radiation is the specification of the quality of the beam of radiation. It is apparent that this consideration applies not only to the interpretation of the results of a weapons test, but also to the planning of future laboratory experiments. From the physical standpoint any beam of radiation is completely specified by a spectral curve of the intensity of all wave lengths within the spectrum of the beam. Project 1.2 measured the gamma-ray spectrum over the range 0.5 to 10 Mev on Dog and Easy Shots. A specification in this detail, however, is not practical for routine use, and a simpler empirical method was employed. Radiation therapists have developed two concepts which are useful for evaluating the amount of radiation absorbed at any position within an animal body. These are the half-value layer (HVL) and the depth dose, which are determined, respectively, by means of filters of increasing thickness, and phantoms. For the biomedical experimentation, the HVL was measured using hollow spheres of lucite which contained film packs and miniature ionization chambers. The depth dose was investigated in laminated masonite phantoms using film packs alone. Two types of masonite phantoms were used, one resembling the volume of a mouse, and the other the volume of the trunk of a pig, or a man. It is believed that a knowledge of the effective energy of nuclear radiation and of the spatial distribution of the dose within a large animal will be useful for the correlation of the biological studies in the field with those using supervoltage X rays, or other sources available in the laboratory. These data should be of value in the design of protective shielding. No measurements of this sort have been made on previous weapons tests.

1.2.5 Clinical Observations

Several types of clinical studies were conducted for the purpose of gaining additional understanding of the pathogenesis of radiation injury due to exposure of the whole body to initial nuclear radiation. It is proper to believe that a knowledge of the manner in which ionizing radiation causes injury and death will facilitate the discovery of protective antidotal or therapeutic agents. The study to which the most importance was attached was the serial-sacrifice experiment. For this study 32 dogs and 32 swine were exposed at a distance where the dose of radiation was expected to be supralethal. At intervals of time varying from a few hours to 10 days after exposure, the injured animals were killed and a careful autopsy performed. It was hoped that the gross and microscopical study would disclose the incipient stages of radiation injury in various tissues in such a fashion that clues would be obtained as to the nature of the injury. Laboratory experiments could then be planned on the basis of such clues. A great deal of effort has been expended on the study of radiation injury due to exposure of the whole body to X rays produced at energies ranging from 200 to 2,000 KVP. On the basis of comparison with material obtained from Japan, and from Bikini, it appears that there is no systematic significant difference between the injury inflicted by an atomic bomb and by hard or supervoltage X rays. In spite of this tentative opinion, there is a real possibility that there may be subtle, but important, differences and that such differences could compromise the value of laboratory studies. In order to explore this question more thoroughly, control studies for the field test were conducted in great detail using the same strain of dogs and swine. It was believed that any additional evidence for the identity of the radiation injury caused by a nuclear weapon

and that caused by X rays was worth obtaining, since many types of experimental study can always be conducted more successfully in the laboratory than in the field.

Since a large number of animals with radiation injury would be available, a small number of clinical studies were planned. These were selected on the basis of the belief that such studies would not compromise either the determination of the MLD, or the serial pathology study. These additional studies consisted of serial blood examination of some of the dogs, aerobic and anaerobic blood cultures from the dogs and the swine sacrificed serially; and the collection at the time of sacrifice of plasma and serum from the dogs for certain biochemical studies. No effort was made to perform a complete detailed clinical pathological study of the animals, since this would have required an exorbitant increase of personnel and technical facilities. The choice of studies was definitely a practical one. In the event of atomic warfare, only a few clinical studies could be done routinely, and it is a consensus that determination of the white blood cell count, the absolute lymphocyte count, the hematocrit, and the concentration of hemoglobin would be adequate for the diagnosis of radiation injury and the emergency management of casualties. Accordingly, these were the only clinical studies performed routinely on the dogs exposed to Easy Shot.

The study of the surviving mice is also considered a clinical study. The survivors of the dose-mortality study (Projects 2.4.1.1 and 2.5.1.2) were sent to Oak Ridge National Laboratory for life-time observation to determine the effect of radiation on longevity, the incidence of cancer, and the incidence of cataracts. Since exposure to neutrons in low dosage is known to induce radiation cataract, several hundred mice were placed in the lead-shielded hemispheres at distances where the dose was expected to be sublethal. The survivors of this study were also returned to the United States to be used for the investigation of the relationship between the dose and the time of development of radiation cataracts. A variety of dosimeters and neutron threshold detectors were exposed in the same geometry as the animals, and ultimately the relationship between effect and dose can be determined.

1.2.6 Study of Thermal Burns

Among the Japanese casualties, flash burns caused by the thermal emission were the most numerous type of injury. The mass treatment of burns is recognized as one of the greatest problems which will confront the medical services in the event of an attack with nuclear weapons. Surprisingly little is known about the characteristics of atomic bomb flash burns, and for this reason the thermal-burn study (Project 2.4.2) was designed to provide some fundamental information which could serve as a basis for more extensive experimental studies. The reaction of living skin to heat cannot be predicted from the study of inert material of comparable composition. Likewise, the physiological sequelae of a burn cannot be predicted by the specification of the incident thermal flux. An important objective of the burn study was the measurement of the physical conditions that produced the burn so that they could be reproduced in the laboratory. These physical conditions included the total incident thermal energy, the rate at which it was delivered, the total time during which burning occurred, and the portion of the spectrum of the thermal emission that caused the burn. Calorimeters were placed in the same geometry as the animal's skin, and were intercalibrated with the instruments of Program 1. Some of the animal exposure stations were located adjacent to physical-measurement stations, where very accurate determinations of total energy, spectrum, etc., were performed. It was assumed that, if all these factors were known, a flash-burn generator could be designed for laboratory use. With a reliable source of thermal injury, it becomes possible to investigate the physiological sequelae in detail. It is also possible to produce small burns in human volunteers and study the most appropriate local treatment.

Another objective of the burn study was the investigation of the time factor. It has been assumed by some writers that the total thermal flux responsible for burning occurs over

a sufficiently long period of time to permit evasive action by trained personnel. The appearance of the flash burns in the Japanese victims, however, suggested that the injury occurred during an interval so brief that no evasive action could have been taken. This is an important point, and one which can be settled only by a field experiment. If successful evasive action can be taken by troops or civilians, a great deal of training effort is justified; if it is not possible, the time can be spent to better advantage.

The animals chosen for the burn study were the Chester White pig and the dog. The skin of this pig resembles human skin to a remarkable extent in its reaction to thermal injury. The dog develops physiological sequelae, such as shock, which are quite similar to those occurring in human subjects after burns of comparable extent. What is even more significant, the shocked dog responds to the same therapeutic measures that are beneficial to man. Both animals are regularly used for experimental studies of burns. The burns produced in the test were small in area, and it was necessary to anesthetize the animals to prevent motion in response to the pain of injury, and to reduce the mimetic reaction of the skin.

1.2.7 Blast Effects

The tactical use of nuclear weapons requires among other considerations that troops shall be sufficiently close to the aiming point to permit rapid occupation of the area of devastation. The distance from the aiming point at which troops can be stationed safely is a matter of dispute at the present time. Protection against flash burn can be accomplished by rather simple means. Protection against radiation injury can be accomplished by placing troops in defilade behind terrain features, or in deep trenches, or in foxholes. A preliminary study of the attenuation of nuclear radiation in shallow foxholes (4 ft deep) made in connection with Operation Ranger, using film packs, demonstrated that the maximum attenuation of gamma radiation from an air burst was by a factor of 10. Although serious air-blast injury was not observed in the Japanese casualties among individuals who took cover in caves and deep air-raid shelters close to ground zero, there has been considerable uncertainty regarding the possible harmful effects of blast in foxholes or shallow trenches within several thousand yards of a detonation of a standard weapon. Since the form of the positive and negative pressure waves produced by a nuclear explosion differs from that caused by high explosive, the tactical planners have not been willing to accept a theoretical solution to the problem based on estimated peak overpressure as a function of distance. For these reasons a simple experiment was planned in which dogs were placed in trenches, 4 ft deep, at distances ranging from 400 to 1,500 yd from Item zero. Since the anatomical lesions of nonfatal air-blast injury may be transitory, all the survivors were sacrificed 12 to 15 hr after the blast, and the vulnerable organs (lungs, brain, and adrenals) were studied.

1.2.8 Summary

The objectives of the biomedical program were distinctly limited. No effort was made to reproduce on a small scale the casualty situation which attends a nuclear explosion. Although it was realized that under ordinary circumstances mixed or multiple injuries would occur, it was decided to study each type of injury in as uncomplicated a form as possible. The greatest effort was devoted to studies which could form the basis for definitive experiments to be conducted in a laboratory environment. Such studies—the determination of the relative biological efficiency of nuclear radiation, depth-dose measurements, and most of the burn study—were almost entirely planned and executed for the benefit of the experimentalists who are seeking to extend our current knowledge of the treatment of whole-body radiation injury and flash burns. The effects of field variables which are unique and which cannot be tested in the laboratory were studied: the mortality rate as a function of distance and dose, the time and spectral dependency of the flash burns, and the blast effects. It is to be expected that the results of this biomedical study will raise more questions than will be answered. It seems likely

that future tests of nuclear weapons will include biological and medical studies which will permit further exploration of the new problems of what has been called "atomic medicine."

1.3 JUSTIFICATION

The principal justification for the conduct of biomedical experiments in a test of nuclear weapons is the lack of precise information on the biological effects of what have been termed the "field variables," viz., blast, thermal radiation, and nuclear radiation. Quantitative measurements of these variables have been made in previous tests, and very precise techniques were developed by Program 1 for use in Operation Greenhouse. Although it may become possible to specify in detail the range and intensity of these phenomena as functions of distance and time, there is no certainty that they can ever be reproduced conveniently in the laboratory. The ideal situation for research in atomic medicine would result if it were shown that the biological effects obtained in the field could be obtained using apparatus easily available. In the event that it is shown that the biological effects are unique, the expense and effort devoted to research which would be necessarily inconclusive could be diverted to field studies. Unfortunately, the science of experimental biology has not advanced sufficiently to permit reliable prediction of the effects which will result from exposure of living systems to physical forces of the sort produced by a nuclear explosion. An empirical study is obviously necessary for the benefit of investigators who are attempting to develop protective antidotal and therapeutic agents for the victims of atomic warfare and accidents in nuclear energy plants. The empirical approach is characteristic of the medical sciences, where ignorance of the mechanism of action of a noxious agent, or a beneficial agent, does not necessarily prevent progress. The information which was sought by the biomedical program was required for the design of future experimentation in radiobiology and medicine, and could not have been obtained in any other way than by a field test.

The parallel development of techniques for atomic warfare and for industrial application of nuclear energy provides a broad base for the need for biomedical studies. The urgent character of this need is due principally to the poor state of international relations which may result in atomic warfare at any time. There is a serious need for biological data which can be applied to the solution of the vast problem of providing adequate medical care for our people in the event of an attack with nuclear weapons. The tactical use of nuclear weapons by U. S. Armed Forces is also dependent to a considerable extent on the type of information that was sought in Operation Greenhouse. Hazards of the industrial type have been controlled in the plants of the AEC by scrupulous safeguards and extreme standards of permissible exposure. The development of more and faster reactors, the advent of nuclear energy plants for the propulsion of aircraft and naval vessels, and the development of nuclear energy plants for the production of electricity increase the possibility of industrial accidents and pose new problems in shielding and the exposure of personnel to radiation. Among these problems is the control of exposure to neutrons, the physical measurement of which is difficult. Equally difficult in the present state of knowledge is the translation of neutron exposure into terms of probable biological effect. It seems likely that every aspect of the application of nuclear energy, as it affects man, will benefit from successful studies of the type that are included in Program 2.

Chapter 2

Summary of Previous Observations

2.1 THE JAPANESE CASUALTIES

2.1.1 Introduction

The staff plans for the atomic bomb attack on Japan included the formation of a team of radiological safety experts from the Manhattan Engineer District under the command of Brig. Gen. C. P. Farrell, USA. The mission of this team was to survey the bombed areas as soon as possible after the anticipated surrender. The team entered Hiroshima and Nagasaki during the 3rd week after the bombing. The members of the team who were physicians conducted a brief study of the casualties on the basis of which they prepared the first report in English of the medical effects of an atomic bomb attack.[1] During the first few weeks after the bombing a number of official preliminary reports were submitted by Japanese medical officers, but these were prepared under exigent circumstances and are of little value.[2] A detailed study of more than 13,000 casualties was carried out by the Joint Commission for the Investigation of the Effects of the Atomic Bomb in Japan in compliance with a directive issued by General Douglas MacArthur, USA, Supreme Commander for the Allied Powers. The results of this study were submitted in a medical report,[3] which was used to advantage in the planning of Program 2, Operation Greenhouse. The material in this section was extracted from the above-mentioned medical report. The weapons used at Hiroshima and Nagasaki were rated at 15 and 20 kt, respectively, and were detonated at altitudes of 1,800 and 1,650 ft, respectively.

2.1.2 The Dose of Gamma Radiation as a Function of Distance

The whole-body dose of gamma radiation which will kill a man of average size is not known from direct experimentation. On the basis of laboratory and field studies using large mammals (swine, goats, and dogs) it has been inferred [4] that the MLD is approximately 400 r, measured in air. The conditions in Japan were such that it was impossible to collect data which resembled the material required for a reliable estimate of mortality rate as a function of dose. In each city, however, small groups were found, the survivors of which reported that: (a) they were shielded only by wooden buildings, (b) they had sustained only radiation injury, and (c) they were able to give a satisfactory circumstantial account of the type of illness and time of death of the remainder of the group, all of whom had been exposed under similar conditions. In Hiroshima, the distance from air zero (AZ) at which such a group was exposed was 3,760 ft, and the mortality rate was 58 per cent.[5] In Nagasaki, the mortality rate was 50 per cent for a comparable group exposed at 3,830 ft from AZ.[6] For purposes of planning Pro-

[1] *The Atomic Bombings of Hiroshima and Nagasaki* (Manhattan Engineer District, 1946).

[2] Translations of these reports are available from the Technical Information Service, USAEC, Oak Ridge, Tenn.

[3] *Medical Report of the Joint Commission for the Investigation of the Effects of the Atomic Bomb in Japan,* 1946, Vols. I–VI, AEC documents NP–3036, NP–3037, NP–3038, NP–3039, NP–3040, and NP–3041.

[4] *The Effects of Atomic Weapons* (Los Alamos Scientific Laboratory and U. S. Government Printing Office, Washington, D. C., 1950), Par. 11–28.

[5] *Medical Report, op. cit.,* Sec. 1, Summary.

[6] *Ibid.*

gram 2, it was assumed that the MLD with a 20-kt weapon would be delivered at about 3,800 ft. According to *The Effects of Atomic Weapons*,[7] the total dose of initial gamma radiation is 800 r at this distance. Basing the diagnosis on the occurrence of the specific symptoms (epilation and/or pupura), clinically significant radiation sickness occurred in individuals exposed as far as 6,800 ft from AZ in each city. At distances greater than this, the incidence and the severity decreased rapidly. Among a large sample of individuals located within 6,800 ft of AZ, and who survived 20 days or more, the incidence of radiation sickness (expressed as per cent of all injuries) was 37.4 per cent in Hiroshima and 33.7 per cent in Nagasaki. The analysis of the occurrence of radiation sickness as a function of distance was complicated by the fact that it was often impossible to determine the extent to which any individual was shielded from the nuclear radiation as a consequence of his location at the time of the bombing.

2.1.3 The Syndrome of Radiation Injury

The Medical Report of the Joint Commission provided reliable criteria for the diagnosis of the syndrome of radiation injury. A most important feature of the syndrome is the relationship between the severity of the injury (or, for practical purposes, the dose) and the tempo of the clinical course and the time trend of the laboratory findings. On the basis of the clinical course alone, it was possible to recognize three patterns that appear to be related to the estimated dose in the following manner: (1) *very severe radiation injury* (Group I in the classification of the pathologist),[8] where the dose certainly exceeds the LD_{90} or LD_{100}; (2) *severe radiation injury* (Group II), where the dose was in the range LD_{10} to LD_{90}; and (3) *moderate or mild radiation injury* (Groups III and IV), where the dose was probably less than the LD_{10}. The hematological studies of the early and late stages of radiation injury were scanty and incomplete.[9] They were useful, however, in the preparation of the clinical description of the syndrome. The time trend of the leukopenia and of the disturbance of coagulation of blood is very characteristic and quite helpful in diagnosis. Specimens were obtained from autopsies performed on patients who died at various times after the 5th day, and the study of this material provided some correlation between the pathogenesis and the clinical course. For the purpose of diagnosis, the specific symptoms and the leukopenia are thoroughly satisfactory for emergency use. The relationship between these clinical symptoms and the leukocyte count for certain groups of patients is shown in Table 2.1. Taken as a whole, the clinical and pathological material collected in Japan demonstrated that the course of radiation injury in man is similar to the course in swine, goats, and dogs.

[7] *Op. cit.*, Fig. 7.42.

[8] A. A. Liebow, S. Warren, and E. deCoursey, "Pathology of Atomic Bomb Casualties," *American Journal of Pathology*, XXV (1949), 853–1028.

[9] G. V. LeRoy, "Hematology of Atomic Bomb Casualties," *Archives of Internal Medicine*, LXXXVI (1950), 691–710.

TABLE 2.1 RELATIONSHIP BETWEEN SYMPTOMS AND LEUKOCYTE COUNT IN EXPOSURE GROUPS, 2ND TO 6TH WEEK AFTER THE BOMBING[a]

	MEAN LEUKOCYTE COUNT			
	Hiroshima Exposure Groups[b]		Nagasaki Exposure Groups	
	A and B	C and D	A and B	C and D
Specific Symptoms				
Epilation and purpura	1,923	2,420	2,181	2,943
Epilation or purpura	2,694	4,157	3,018	2,975
Suggestive Symptoms Only	3,980	5,944	4,511	5,006
No Symptoms	4,791	6,268	5,148	5,839

[a] Taken from *Medical Report, op. cit.*, Vol V, NP-3040, Tables 57H and 57N.

[b] Exposure Groups consisted of individuals who were assumed to have received comparable doses of radiation. Groups A and B were persons outdoors or in wooden buildings within 4,950 ft of GZ, and persons in heavy buildings within 3,300 ft of GZ. Groups C and D were persons outdoors or in wooden buildings from 4,950 to 7,250 ft from GZ, and persons in heavy buildings from 3,300 to 6,600 ft from GZ, and persons in bomb shelters and tunnels within 3,300 ft of GZ.

Unfortunately, the Japanese data were not available in sufficient amount or detail to be of much value in planning a rational therapeutic regimen for radiation sickness.

2.1.4 The Study of Flash Burns

The largest number of severe injuries in Japan were burns. The incidence of flash burns is shown in Table 2.2 for individuals who survived 20 days or more, who were outdoors at the time of the bombing, and who were within 13,300 ft of AZ. The greatest distances from AZ at which burns were reported were 15,000 ft in Hiroshima and 13,300 ft in Nagasaki. The burns that were sustained by individuals at distances greater than 11,000 ft seldom required medical attention, since they consisted mainly of an erythema. Histological specimens were not obtained during the early course of any burn in Japan. During the stage of healing, peculiarities of pigmentation were observed, the significance of which could not be evaluated. Equatorial burns of the cornea were infrequent, and only a few ecliptic burns of the retina were seen.[10] These latter observations have some bearing on the time dependency of the burning portion of the thermal emission, but no conclusions regarding its duration can be drawn from the Japanese data. An estimate of the amount of heat delivered to the skin as a function of distance can be made from measurements performed at weapons tests. A comparison of these estimates with the appearance of burns on admission to hospital was possible in the case of a group of 44 patients whose location at the time of bombing was known. These patients were burned in Nagasaki at 1100 hr, 9 August, and the surgeon's description of the lesions was made approximately 12 hr later. These data are given in Table 2.3, and it can be seen that the estimates of incident thermal energy are consistent with the type of lesion produced. This group of patients is of interest since the burns are described in objective terms. Most of the entries in the original clinical records refer to the burns as first, second, or third degree, but the criteria used are not given.

The Japanese clinical records contain no specific information on the physiological disturbances that occurred as sequelae to ex-

TABLE 2.2 INCIDENCE OF FLASH BURNS IN INDIVIDUALS WHO SURVIVED 20 DAYS OR MORE, AND WHO WERE OUTDOORS AT THE TIME OF THE BOMBING, WITHIN 13,300 FT OF AZ [a]

	NUMBER OF PERSONS			PER CENT BURNED	
	In Study	In Sample[b]	Burned	Per Cent of Sample	Per Cent of All Injuries
Hiroshima	6,396	1,985	1,596	80.4	89.9
Nagasaki	5,927	884	539	61.0	78.3

[a] Taken from *Medical Report, op. cit.*, Summary, p. 14.
[b] Sample consisted of all individuals interviewed who stated they were outdoors unshielded at the time of the bombing.

[10] *Medical Report, op. cit.*, Vol. II, NP-3037, Section 5H, p 14.

TABLE 2.3 APPEARANCE OF FLASH BURNS ON ADMISSION TO THE OMURA NAVAL HOSPITAL, 9 TO 10 AUGUST[a]

RANGE OF DISTANCE FROM ZERO (ft)	ESTIMATED INCIDENT TOTAL THERMAL RADIATION IN FIRST SECOND (cal/cm²)			APPEARANCE OF BURNED SKIN		
	Max[b]	Min	EAW[c]	Exfoliated	Exfoliated and Vesiculated	Vesiculated
2,800–3,300	150	25	75	7	2	1
3,300–4,950	37	11	30	6	2	3
4,950–6,600	16	6	18	6	2	5
6,600–8,250	9	4	10	3	3	4

[a] Taken from *Medical Report, op. cit.*, Vol. II, NP-3037, Section 5N, Table 7.
[b] Personal Communication, V. H. Weisskopf.
[c] *The Effects of Atomic Weapons, op. cit.*, Fig. 6.36, p 194, $k=0$.

tensive burns. The case-fatality rate for severe burns was difficult to estimate, since all patients with serious flash burns also received some gamma radiation. The case-fatality rate was 50.3 per cent for a group of 177 patients with burns comparable in severity to those cited in Table 2.3 and treated in an excellent naval hospital. The late results of flash burns have been studied by experts under the auspices of the Atomic Bomb Casualty Commission of the National Research Council. According to the official report, the healed flash burns were no different than ordinary healed burns of similar extent and depth.[11]

2.1.5 Injuries due to Blast

Evidence of primary air-blast injury was not observed in Japanese casualties, with the exception of ruptured ear drums. The overpressure required to rupture the human ear drum varies from 3.5 to 20 psi, with an average value of 7. This amount of overpressure is considerably less than that required to cause primary air-blast injury of the lungs. Secondary air-blast injury is the term applied to such consequences of an explosion as violent displacement of the patient, injury from flying debris and secondary missiles, and crushing injuries in collapsed buildings, etc. In Japan, mechanical injuries of this sort were common, but did not differ materially from those observed in conventional warfare and in civil accidents.

2.1.6 Casualty Rates

The effectiveness of an atomic bomb as a casualty-producing weapon is shown in Table 2.4. The standardized casualty rate (SCR) and the standardized killed rate (SKR) describe both the weapon and its human target. These rates are computed by adjusting the actual casualty rate and killed rate in the area at risk (in the case of the Japanese cities, the area was taken to be 30 square miles) to a standard urban population density of 43 per acre. The higher SCR for the weapon used at Hiroshima is probably due to the fact that the population at risk was less well protected by heavy building construction than was the case in Nagasaki. The case-fatality rate is a complex resultant of the type of injuries that occurred and the quality of medical care that was rendered. For comparison, the crude case-fatality rate for civilians in London during the blitz was 15 per cent. For U. S. forces in Korea in 1950–1951, the crude case-fatality rate was 20 per cent; and for Korean civilians during the same period, the rate was 60 per cent.[12]

TABLE 2.4 CASUALTY RATES[a]

	SCR PER BOMB	SKR PER BOMB	CRUDE CASE-FATALITY RATE (per cent)
Hiroshima 15-kt bomb	261,000	79,500	30
Nagasaki 20-kt bomb	131,000	75,300	56

[a] Taken from *Medical Report, op. cit.*, Vol VI, NP-3041, Sections 10H and 10N.

2.1.7 Summary

The study conducted by the Joint Commission was successful in describing the conditions that existed after an atomic bombing. The development of criteria for the clinical diagnosis of radiation injury was important. Many problems associated with the provision of adequate medical care were suggested, and few of them could be answered with the data available in 1945–1946. The Medical Report of the Joint Commission clearly demonstrated that there was a need for a large amount of medical research into the nature and the treatment of the injuries caused by nuclear and thermal radiation. In the succeeding portion of this chapter, some of the efforts to meet this need will be described.

[11] *Report of Atomic Bomb Casualty Commission* (National Research Council, 1948).

[12] *Time*, 12 February 1951; based on report of 7,739 military dead, 29,819 military wounded, 163,461 civilian dead, and 104,722 civilian wounded.

2.2 OPERATION CROSSROADS, 1946

2.2.1 Introduction

Operation Crossroads was carried out in June 1946 at Bikini Atoll to study the effect of an air burst and an underwater burst on naval vessels and on their operating personnel. The primary objective of the medical program was to determine the extent and the kind of radiation injury sustained by experimental animals displayed in locations on the ships normally occupied by personnel. Important secondary objectives included a study of certain protective measures and the exposure of selected biological material of interest to radiobiologists. The animals chosen for the experiment and the numbers available at test time were: 200 swine, 200 goats, and 5,000 white rats. These were housed in adequate quarters aboard the *USS Burleson,* which had been modified to serve as a laboratory ship. About 75 personnel participated in the conduct of the medical experiments.[13]

2.2.2 Test Able

The first test was an air burst of a 20-kt weapon, detonated at an altitude of approximately 500 ft. Animals were placed on 22 of the target vessels, which were stationed along several radii at various distances from the aiming point. The large animals were arranged in groups of two or three in pens; the rats were in cages containing 10 or 12. These were located throughout the ships from the holds to the lookouts on the masts. Swine were the large animals used below deck, and goats, which tolerate heat better, were placed on the weather decks. In accordance with the objective, animals occupied every position on some one of the ships where men would be stationed during General Quarters. Some of the goats that were placed in exposed positions where burns could occur were shaved. The arrangement of the animals on the ships was such that an estimate could be made of the distance at which the MLD was delivered.

Unfortunately, the air drop was off target by some 500 yd. As a result of this, nearly all the unshielded animals along one radius received radiation equal to, or greater than, the $LD_{100/30}$, and the majority of the remainder received amounts less than the MLD. In spite of this, it was possible to make a fair estimate of the distance at which the MLD was delivered to the large animals. With the weapon used in Test Able, this distance was about 3,600 ft, a value that agrees well with the estimates for man in Japan, with weapons of comparable kiloton ratings. It was not possible to obtain good data on after-survival time as a function of dose, but it appeared that the duration of life after equivalent exposures was similar for man and swine. Among the animals recovered from the target ships there was a marked variation in the severity of the radiation injury exhibited by the several members of a group exposed at the same position. One might receive a lethal dose, and the others appear to be unharmed. Such variation is an expression of the potentially great amount of shielding that is afforded by the complicated arrangement and heavy construction of naval vessels. For this reason, it is impossible to predict the incidence and the severity of radiation injury to personnel aboard a warship exposed to an air-burst atomic bomb.

The clinical pattern of the severe radiation injury that developed in large animals who received a lethal dose was found to resemble closely the effects of equivalent amounts of supervoltage X rays.[14] This observation was very important, since it tended to validate the use of hard X ray (particularly X rays produced at 1,000 to 2,000 KVP) for experimental studies. The histopathological material that was obtained was excellent, and the study of

[13] The material in this section was derived from published reports of the Director of Ship Material, Bureau of Medicine and Surgery Research Group, U. S. Navy, and from personal communications from members of the Group.

[14] John L. Tullis and Shields Warren, "Gross Autopsy Observations in the Animals Exposed at Bikini," *Journal of the American Medical Association,* CXXXIV (1947), 1155–58; and John L. Tullis, Carl F. Tessmer, Eugene P. Cronkite, and F. W. Chambers, Jr., "The Lethal Dose of Total Body X-Ray Irradiation in Swine," *Radiology,* LII (1949) 396–400.

it demonstrated the essential similarity of the lesions of radiation sickness in man and swine. Autopsies were performed only on animals that died spontaneously, so that the evolution of the response of the tissues could not be studied. The hematological study [15] provided good data on the magnitude and the time trend of the leukopenia, lymphopenia, thrombocytopenia, and anemia that are characteristic of radiation injury. In the swine especially, the changes in the blood of the irradiated animals resembled closely the findings among the Japanese casualties. At Operation Crossroads, it was possible to obtain good samples of blood during the early stages of the syndrome when comparable material was not available in Japan. Special attention was directed to the hemorrhagic state which is typical of severe radiation injury, and the unique character of this process was established.

The hairy coats of the goats and rats protected them from flash burns at all distances greater than 2,000 ft from zero. The goats that were shaved sustained serious burns unless the skin was protected by the flash cream provided for the gun crewmen of U. S. warships. Primary air-blast injury was observed in rats placed on the weather decks and in the rigging at distances less than 4,800 ft from zero, but it was not observed in any of the goats.

Among the other biological materials exposed to Test Able, the most interesting results were obtained from the growth and genetical studies of corn seed and *Neurospora.* In the case of *Neurospora,* the yield of biochemical mutations was greater than had ever been obtained by a single exposure to X rays. The somatic mutations of the corn were unique, and it has not been possible to reproduce the genetic damage with single exposures to the usual laboratory sources of radiation.

[15] E. P. Cronkite, "Statistical Analysis of Hematological Data on Pigs," Appendix 5 to the final report, Operation Crossroads, Director of Ship Material, Bureau of Medicine and Surgery Research Group; and *Idem,* "The Hemorrhagic Syndrome of Acute Ionizing Radiation Illness Produced in Goats and Swine by Exposure to the Atomic Bomb at Bikini," *Blood,* V (1950) 32–45.

2.2.3 Test Baker

Groups of 10 pigs and 25 rats were placed in the sick bays of each of two ships stationed at 716 and 1,326 yd from zero, respectively. The animals could not be recovered after the underwater burst until the 4th and 5th days. The animals on the closer ship were recovered on the 4th day, at which time six of the pigs were dead; the remainder died on the following day. The total dose of residual gamma radiation was estimated to be of the order of 20,000 r. The animals on the more distant ship were recovered on the 4th and 5th days, at which time all were alive. They all died, however, between the 8th and the 14th day after the explosion. The estimated total dose of residual gamma radiation at this location was 1,500 r. The histopathological lesions due to radiation sickness in these swine were similar to those observed after Test Able. The study of the rats was complicated by the occurrence of an epidemic disease, which seriously affected the interpretation of the results.

2.2.4 Summary

The animal experiments of Operation Crossroads supplied important data for medical planning and for the design of later investigations. The most significant result was the demonstration of the similarity of the response of man and swine to lethal doses of initial nuclear radiation. Equally significant was the demonstration of the essential similarity of the response of swine to lethal doses of nuclear radiation from an atomic bomb and X rays produced at 1,000 to 2,000 KVP. These similarities were a source of encouragement to medical research workers and justified the continued use of suitable large animals for experimental pathology and experimental therapy. The studies at Bikini provided data which served to confirm and complement the clinical study of the Japanese casualties.

2.3 OTHER WEAPONS TESTS

Biological studies were not performed at Operation Trinity in 1945. At Operation Sandstone, a small number of seeds and

moulds were exposed, and preliminary studies were conducted on cylindrical tanks for the exposure of large animals. These studies may be considered as preliminary to the biomedical program of Operation Greenhouse, since the final design of the cylindrical stations was developed from them. No biological specimens were exposed in Operation Ranger because it was conducted during the preparatory phase of Greenhouse. Measurements were made of the attenuation of gamma radiation in foxholes, and these were the preliminary study for the experiments conducted on Item Shot at Operation Greenhouse.

2.4 SUMMARY

The biological and medical studies that were made in connection with the detonation of atomic bombs prior to Operation Greenhouse provided interesting but incomplete data on a large number of subjects. The most valuable information was obtained from the study of the Japanese casualties, although of necessity this study was inconclusive. The previous observations did provide some information on the field variables of a nuclear explosion and served as the necessary background for planning the biomedical program of Greenhouse.

Chapter 3

Theoretical Considerations

3.1 INTRODUCTION

In this section each of the field variables to be studied is considered separately with respect to its expected intensity and the design of the experiment in which it was studied. The values for intensity were based on theoretical calculations scaled to the anticipated yield for each weapon. The source of the values used in planning was the *Biomedical Experimenter's Handbook,*[1] and the *Greenhouse Handbook.*[2] All the experiments were planned to permit the acquisition of good data if the actual yield varied no more than ±20 per cent. In general, the attempt was made to study separately the effects of nuclear radiation, thermal radiation, and blast. The attempt was successful in the case of nuclear radiation, and at the distant thermal stations. At the close-in thermal stations and the blast stations, it was not convenient to design equipment which would exclude other forces than the one of principal interest. In this section the theoretical intensity of each field variable as a function of distance is considered independently of any attenuation or modification that might result from the type of equipment in which the biological material was placed for exposure.

[1] *The Biomedical Experimenter's Handbook,* Los Alamos Scientific Laboratory, Classified Document. This document has been replaced by the *Green-House Handbook.*

[2] *Greenhouse Handbook of Nuclear Explosions, Part I, Theory* (Los Alamos Scientific Laboratory, LAB-J-2182, 1951).

3.2 INITIAL NUCLEAR RADIATION AS A FUNCTION OF DISTANCE

3.2.1 Gamma Rays

Since the RBE of the gamma radiation was not known it was assumed to be unity with respect to X rays of the order of 200 to 2,000 KVP. The distances from zero at which specimens were placed were based on the predicted dose of gamma rays as follows:

$$\text{Dose (r)} = 2.9\times10^{9}\,\frac{we^{-D/\lambda}}{D^{2}} \qquad (3.1)$$

where

w = yield in kilotons
D = distance from the explosion in meters
λ = mean free path in meters, as given by $\lambda = 283(1+T/273)$, where T = air temperature in degrees centigrade.

There is reason to believe that the values obtained by the use of this formula are too low, and a correction factor of 1.7 has been applied by Suydam to the film data obtained in previous weapons tests.[3] The value for the mean free path is also under review. When the station locations were planned, the prediction of dose was not corrected. The predictions of yield that were used in planning were the best available at the time, and were as follows: Dog, 140 kt; Easy, 50 kt; George, 250 kt; and Item, 50 kt. Mice, swine, dogs, and *Tradescantia* were placed at distances where the predicted dose, uncorrected, varied from 2,600 to 140 r. It was assumed that this range would yield sufficient points for the construction of dose-mortality curves and would include the range of

[3] *Greenhouse Handbook, op. cit.,* Par. 4.2.2.

dose for which the biological materials and the depth dosimeters were adapted. The locations of the stations for the determination of the effect of gamma rays as a function of distance are given in Tables 3.1, 3.2, and 3.3 for Dog, Easy, and George Shots, respectively. It was appreciated that these uncorrected values for dose were first approximations and that the use of correction factors, values other than 283 meters for the mean free path, and the ±20 per cent variation in the expected yield of the weapon could alter the actual dose by a factor of 2 or more. These uncertainties were responsible, for example, for the large number of mouse stations employed on

TABLE 3.1 GAMMA RADIATION AS A FUNCTION OF DISTANCE, LOCATION OF STATIONS FOR DOG SHOT
(Predicted Yield: 140 kt)

STATION NO.[a]	DISTANCE (yd)	ESTIMATED DOSE (r)	
		Uncorrected	Corrected
74a	1,550	1,150[b]	1,955[c]
b	1,575	960	1,632
c	1,635	730	1,241
d	1,670	555	944
e	1,720	475	808
f	1,775	365	621
g	1,850	270	459
h	2,100	210	357

[a] The biological material exposed in these stations consisted of mice for determination of thymus-spleen weight change, and *Tradescantia*.

[b] *Biomedical Experimenter's Handbook, op cit.*, Supplementary Table.

[c] Correction factor, ×1.7, as suggested in *Greenhouse Handbook, op. cit.*, Par. 4.2.2.

TABLE 3.2 GAMMA RADIATION AS A FUNCTION OF DISTANCE, LOCATION OF STATIONS FOR EASY SHOT
(Predicted Yield: 50 kt)

STATION NO.[a]	DISTANCE (yd)	ESTIMATED DOSE (r) [b]	
		Uncorrected	Corrected
70a	1,075	2,600	4,420
b	1,200	1,530	2,601
c	1,260	1,150	1,955
d	1,300	960	1,632
e	1,315	890	1,513
f	1,328	850	1,445
g	1,336	810	1,377
h	1,344	790	1,343

TABLE 3.2 (*Continued*)

STATION NO.[a]	DISTANCE (yd)	ESTIMATED DOSE (r) [b]	
		Uncorrected	Corrected
i	1,352	760	1,292
j	1,360	730	1,241
k	1,368	695	1,182
l	1,376	680	1,156
m	1,384	655	1,114
n	1,392	630	1,071
o	1,400	600	1,020
p	1,408	590	1,003
q	1,416	575	978
r	1,424	555	944
s	1,432	535	910
t	1,440	520	884
u	1,460	475	808
v	1,490	410	697
w	1,520	365	621
71a	1,555	315	536
b	1,590	270	459
c	1,625	245	417
d	1,650	210	357
e	1,750	140	238
72h[c]	1,354	750	1,275
a	1,400	600	1,020
83	1,434	525	893
72b	1,444	500	850
c	1,488	415	706
d	1,532	340	578
e	1,576	290	493
f	1,620	240	408
g	1,655	205	349
i	1,750	140	238
74a[d]	1,260	1,150	1,955
b	1,300	960	1,632
c	1,360	730	1,241
d	1,424	555	944
e	1,460	475	808
f	1,520	365	621
g	1,590	270	459
h	1,650	210	357
80a[e]	900	7,500	12,750
b	1,260	1,150	1,955
c	1,460	475	808
d	1,645	220	374
e	6,810	29	49

[a] The biological material exposed in these stations consisted of mice for the dose-mortality study, mice for the determination of thymus-spleen weight change (some stations), and *Tradescantia* (some stations).

[b] Estimates of dose are on the basis cited in Table 3.1.

[c] The biological material exposed at these stations consisted of swine and dogs.

[d] The biological material exposed at these stations consisted of mice for the determination of thymus-spleen weight change.

[e] Phantoms only were exposed at these stations.

TABLE 3.3 GAMMA RADIATION AS A FUNCTION OF DISTANCE, LOCATION OF STATIONS FOR GEORGE SHOT
(Predicted Yield: 250 kt)

STATION NO.	DISTANCE (yd)	ESTIMATED DOSE (r) [b]	
		Uncorrected	Corrected
74a[a]	1,620	1,330	2,261
b	1,650	1,050	1,785
c	1,690	920	1,564
d	1,730	780	1,326
e	1,775	650	1,105
f	1,830	540	918
g	1,910	400	680
h	2,160	230	391
80c[c]	1,800	590	1,003
d	2,160	230	391

[a] The biological material exposed at these stations consisted of mice for the determination of thymus-spleen weight change.
[b] Estimates of dose are on the basis cited in Table 3.1.
[c] Phantoms only were placed at these stations.

Easy Shot. Actually the limitation on the number of stations for any shot was imposed by the number of animals on hand and the number of personnel available to move them to and from the shot islands.

3.2.2 Neutrons

The total number of neutrons as a function of distance is not known for weapons of the types studied at previous tests.[4] Estimates are available, however, which may be in error by as much as a factor of 3. When the location of stations for the exposure of mice and *Tradescantia* was planned, it was necessary to make a number of assumptions, not only with respect to the neutron dose but also with respect to the biological effect of the neutron spectrum emitted by the weapon. The ratio of fast to slow neutrons was taken as 0.1. The estimates of slow neutrons per square centimeter per kiloton were those obtained at Operation Sandstone.[5] It was assumed that 1 rem is equal to 10^{10} slow neutrons per cm^2 and 1.6×10^8 fast neutrons per cm^2. The lead dome of the hemisphere station was assumed to be opaque for gamma rays and to permit the passage of most of the neutrons. The neutron stations for Dog Shot were located on the basis of a predicted yield of 140 kt, and the expected dose of neutrons at the four distances chosen ranged from about 1,100 to 100 rem. For Easy Shot, with a predicted yield of 50 kt, the range of dosage at eight distances was expected to be from 1,100 to 10 rem. The actual yield for Dog Shot was approximately 90 kt, or 65 per cent of the value used to plan the location of the stations. The results of the experiments with mice and *Tradescantia* were much more satisfactory then, than in the case of Easy Shot, where the biological studies indicated neutron effects greater than were predicted. On the basis of this experience, the stations for George Shot were relocated to distances from zero where the expected dose would resemble that obtained with Dog Shot. The location of the neutron stations is given in Table 3.4 for Dog, Easy, and George Shots, respectively. The expected dose at the various stations is not tabulated, since all concerned realized that it was at best a first approximation for planning purposes.

TABLE 3.4 NEUTRONS AS A FUNCTION OF DISTANCE, LOCATION OF STATIONS

STATION NO.[a]	DISTANCE (yd)		
	Dog	Easy	George
73a	900	675	1,000
b	900	675	1,050
c	1,000	700	1,100
d	1,000	700	1,150
e	1,100	775	1,200
f	1,100	775	1,250
g	1,200	875	1,300
h	1,300	1,000	1,350
i			1,400
j			1,450
85a		675	1,250
b		775	1,350
c		875	1,450
d		975	1,500
e		1,100	1,600
f		1,300	1,650

[a] The biological material exposed at these stations consisted of mice for determination of thymus-spleen weight change, series 73, and mice for study of cataracts, series 85. The lead dome of 73b, d, and f stations was covered by a sheath of cadmium, 1/32 in. thick.

[4] *Greenhouse Handbook, op. cit.*, Par. 5.3.
[5] *Greenhouse Handbook, op. cit.*, Fig. 5.2.

3.2.3 Mixed Radiation

At Operations Crossroads and Sandstone, corn seeds, *Neurospora,* and other botanical specimens were exposed to very high doses of nuclear radiation, close to zero. The yield of mutations was unusually large, and provided valuable material for genetic studies. To continue such studies, corn and another mould, *Glomerella,* were exposed close to zero on Easy Shot. For these studies the actual dose may be less critical than the fact that the dose was very large and was delivered during a relatively short time. The location of the "standpipe" stations in which this material was exposed, and tentative estimates of dose based on the *Biomedical Experimenter's Handbook* are given in Table 3.5.

TABLE 3.5 TOTAL NUCLEAR RADIATION AS A FUNCTION OF DISTANCE, LOCATION OF STATIONS FOR EASY SHOT
(Predicted Yield: 50 kt)

STATION NO.	DISTANCE (yd)	ESTIMATED DOSE[a]		
		Neutrons (rem)	Gamma Rays (r)	Total (rem)
84a	300	56,000	600,000	656,000
b	400	12,000	235,000	247,000
c	500	8,000	100,000	108,000
d	650	1,200	35,000	36,200
e	725	700	22,000	22,700
f	800	400	13,500	13,900

[a] Taken from *Biomedical Experimenter's Handbook, op. cit.,* Supplementary Table.

3.3 THERMAL RADIATION

The field study of burns caused by thermal radiation consisted of three parts: clinical examination of the burns, spectral dependency, and time dependency. Fairly precise data are available for the total incident thermal energy as a function of distance,[6] for the fraction of total thermal energy emitted vs time,[7] and for the fireball illumination as a function of time.[8] In planning the location of thermal stations, it was assumed that clinical burns were sustained during the first second at which time approximately 60 to 70 per cent of the total thermal radiation had been emitted. On the basis of control experiments in the laboratory, it was considered that 1.6 cal/cm²/sec would cause an erythema; 3.0 cal/cm²/sec, a second-degree burn; and 6.0 (or more) cal/cm²/sec, a third-degree burn. The locations of the thermal stations and the expected thermal radiation during the first second are given in Table 3.6. The distances chosen were compatible with the observation of the occurrence of burns among the casualties at Hiroshima and Nagasaki. At the closest thermal station, No. 75 for Easy and George Shots, it was not feasible to provide complete shielding of the gamma radiation. The flanks of the experimental animals at this location were exposed to approximately 500 r. The remainder of the animal's body was protected by at least 12 in. of coral concrete. It was anticipated that the animals in the forward station would be fatally injured by gamma radiation, but it was expected that they would survive long enough to permit adequate clinical study of the burns.

The determination of the spectral character of the thermal radiation was one of the projects of Program 1. The biological effect of various portions of the spectrum was investigated by means of broad-band filters which

TABLE 3.6 THERMAL RADIATION AS A FUNCTION OF DISTANCE, LOCATION OF STATIONS FOR EASY AND GEORGE SHOTS

STATION NO.	DISTANCE (yd)	APPROXIMATE INCIDENT THERMAL ENERGY (cal/cm², first sec)	
Easy Shot (50 kt)			
75	1,325	50[a]	75[b]
76	2,270	30	45
77	3,090	12	24
78	3,500	10	18
78a	4,400	6	
79	5,330	3	5.5
George Shot (250 kt)			
75	3,460	60	90
76	4,785	35	43

[a] Estimates from *Greenhouse Handbook, op cit.,* Fig. 6.25, using $k=0$.
[b] Estimates in Greenhouse Report, Annex 2.2, Part IX.

[6] *Greenhouse Handbook, op. cit.,* Fig. 6.25.
[7] *Ibid.,* Fig. 6.21.
[8] *Ibid.,* Fig. 6.20.

permitted the exposure of the animal's skin to the infrared (Corning No. 2404); the visible (Pittsburgh heat-absorbing glass); and the ultraviolet (Corning No. 9863 combined with a cell containing 60 per cent W/V solution of nickel sulfate). The burns that occurred beneath these filters could be compared readily with burns caused by the total thermal radiation through optically plane quartz windows. To permit evaluation of the burns received through the filters, long-time constant bolometers were placed in the same geometry as the animals behind similar filters. These bolometers were intercalibrated with the equipment used for Program 1.

The variation of thermal radiation with time has been carefully measured at previous weapons tests, and the characteristic curves are available. The portion of the thermal emission (in a time sense) which inflicts the burn is not known from direct experiment. On the basis of clinical observations made in Japan, several inferences have been made:

(a) Since burns of the cornea were infrequent in human subjects, burning did not occur prior to the reflex closing of the eyelids. The blink reflex in man requires at least 25 msec.

(b) All the burns had very sharp margins, which was taken to indicate that burning was completed prior to mass reflexes of an evasive type, such as turning the head, raising the hands to shield the eyes, falling to the ground, etc. Mass reflexes of this sort require 100 to 500 msec in man.

(c) Burning of persons and combustible surfaces appears to have been completed prior to the arrival of the blast wave. For a nominal atomic bomb, the shock front arrives at 1,000 yd in approximately 1 sec.

On the basis of the foregoing it has been assumed that clinical burns occurred during the first portion of the second maximum. However, the curves for fireball illumination as a function of time suggest that burning could continue for at least 2 to 3 sec, and this has suggested to some writers that evasive action could be taken by trained personnel. In the case of living skin, very prompt reflexes occur in response to painful stimuli which result in an increased blood flow through the skin and a greater dissipation of heat than in the intact state. Because of physiological variables such as this, a theoretical treatment of the time-dependency problem is almost impossible. Experimental data were sought by means of fast and slow shutters, using the actual burn of the skin as the indicator. Measurements of this sort are at best first approximations and leave many aspects of the problem unsolved.

3.4 BLAST

The effects of blast on man and large experimental animals have been studied extensively with respect to high explosives. When the blast is received face on, man, goats, large dogs, etc., can tolerate overpressures in excess of 50 psi or more with little injury except to the ear drums. In Japan, at distances where individuals survived, whether in the open or in air-raid shelters, the only evidence of injury due to air blast was ruptured ear drums. Since it is possible to provide adequate protection from thermal injury and radiation injury by appropriate shelters, it becomes important to determine the physiological effect of air blast from a nuclear explosion. The shock wave associated with a given amount of overpressure from an atomic bomb differs from that due to high explosive only with respect to the duration of the positive and negative phases. The lethal effects of air blast in animals are caused by rupture of pulmonary alveoli, by an abruptly increased venous pressure in tributaries of the vena cava system, and by direct compression of the body. The increased venous pressure is caused by direct transmission of the increased intrapulmonary and intra-abdominal pressure to the blood in the pulmonary artery, the right auricle, and the vena cava system. As a consequence of this sudden increase in hydrostatic pressure, hemorrhages may occur anywhere in the capillary bed. Sudden death due to blast is probably caused by cardiovascular reflexes induced by the change in hydrostatic pressure, whereas delayed death is due to injury to the lungs, central nervous system, adrenals, and heart. For a given amount of overpressure, it seems

probable that the damage will be proportional to the length of time it is maintained. For this reason, air-blast injury from a nuclear explosion may be more severe than that caused by a high explosive such as TNT.

For the study of blast effects, dogs were placed in foxholes 4 ft deep. It was assumed that the overpressure within these trenches was the same as the reflected peak overpressure on the ground at the same distance from the tower. In planning the experiment, the expected yield of Item Shot was taken as 50 kt, and the overpressure as a function of distance was obtained from a theoretical curve.[9] Preliminary experiments conducted at Operation Ranger demonstrated that the attenuation of gamma radiation (measured with NBS film packs) in holes 4 ft deep did not exceed a factor of 10 and was generally less. The conditions of overpressure and radiation dosage anticipated for the dogs in the foxholes are given in Table 3.7. The construction of the foxholes was such that the animals were not exposed to the thermal radiation from the fireball.

[9] *Greenhouse Handbook, op. cit.,* Fig. 6.5.

TABLE 3.7 AIR BLAST AS A FUNCTION OF DISTANCE, LOCATION OF STATIONS FOR ITEM SHOT
(Predicted Yield: 50 kt)

STATION NO.	DISTANCE (yd)	REFLECTED PEAK OVERPRESSURE (psi) [a]	GAMMA-RAY DOSE÷10 (r) [b]
86a	400	180	23,500
b,c	600	50	6,000
d,e	800	26	1,620
f	1,000	17	520
g	1,250	12	138
h	1,500	8	50

[a] *Greenhouse Handbook, op. cit.,* Fig. 6.5.

[b] *Biomedical Experimenter's Handbook, op. cit.,* Supplementary Tables. The division factor for attenuation in a hole 4 ft deep is a personal communication from B. R. Suydam.

Chapter 4

Description of Procedure

4.1 JAPTAN ISLAND

All the activities concerned with the biomedical program were located on Japtan Island, Site L. Animal quarters, the laboratory, living quarters for the personnel, and adequate utilities were installed between September 1949 and July 1950. A description of the laboratory facilities is given in Greenhouse Report, Annex 2.1, Part I, and of the animal colony in Part II. Sufficient equipment and supplies were on hand at shot time to accomplish the mission of Program 2. The island laboratory and its supporting activities, as well as the animal colony, were the responsibility of a small detachment of naval personnel designated as Bumed Unit One. This unit was activated in November 1949 by the Bureau of Medicine and Surgery, Department of the Navy, and was under the administrative supervision of the Naval Medical Research Institute.

4.2 ANIMAL COLONY

The ad hoc committee which prepared the first draft of the protocol for Program 2 recommended that experimentation should be limited to animals of three species: mice, swine, and dogs, all of which had been born and reared on Eniwetok Atoll. The provision for the rearing of all test animals in the tropical environment was introduced for the following reasons:

(*a*) *Acclimatization.* It is generally recognized that physiological disturbances may accompany marked environmental changes. Such changes were observed in the animals used in Operation Crossroads at Bikini Atoll, and serious difficulty in the interpretation of data resulted.[1]

(*b*) *Establishment of equilibrium with new diseases.* Since the tropical environment is abnormal for the strains of animals that were used, and since exposure to infections in wild strains of the same species and from other sources might be encountered, it was anticipated that the introduction of test animals into the tropics would result in an increased incidence of infection. Such an increase occurred in the animals taken to Bikini. The easiest and most satisfactory way to accomplish total acclimatization of the sort contemplated was to establish an animal colony at Eniwetok where the test animals could be born and raised. In the case of mice, it was feasible to use test animals whose ancestors had lived on Japtan for five generations, that is, since November 1949, when the breeding stock arrived. In the case of swine and dogs, the longer period of gestation would not permit such complete acclimatization. It was possible, however, to import breeding stock in July 1950. Actual breeding was not started for several months after this, when it appeared that the animals had become well adapted to the new environment. All of the swine and most of the dogs used in the tests were born on Japtan.

The animal colony was a successful solution to the problem of supplying at shot time approximately 14,000 mice, 200 swine, and 200 dogs. All the animals were reared in good quarters in a healthy environment with no possibility of contact with wild strains which might transmit infective diseases. The con-

[1] Report of Special Panel of Officers, NRDL, September 1949.

stant attention of a qualified officer of the Veterinary Corps, USA, was an important factor in the successful production of adequate numbers of healthy animals.

4.3 CHOICE OF BIOLOGICAL SPECIMENS

4.3.1 Mice

Mice are prolific, easy to raise, and easy to handle. A highly inbred, homogeneous stock can be established readily which will respond in a predictable manner to appropriate biological and physical agents. They are particularly well suited for experimentation, which requires large numbers of subjects and biometrical treatment of the data. The most satisfactory strains for radiobiological research appear to be first generation hybrids resulting from the crossing of two highly inbred strains. The hybrid mouse used in Operation Greenhouse is designated "LAf_1", the product of mating females of the L strain with A males. The L strain (for leaden color) was developed at Iowa State College as a mutation which bred true. The original breeding stock for the animal colony consisted of one pair that belonged to the 52nd inbred generation of this strain, and was obtained from the National Cancer Institute, National Institutes of Health, Bethesda, Maryland. The A strain (for albino color) was developed in the laboratory of C. C. Little, Bar Harbor, Maine, as a tumor-bearing mutation from the 57th generation of his C strain. The original breeding stock for the animal colony consisted of one pair which belonged to the 86th inbred generation of the A strain, and also was obtained from the National Institutes of Health. The first generation hybrid of these strains (LAf_1) appears to be one of the best mice developed to date for research in radiobiology because of its consistent reaction to ionizing radiations.[2]

[2] Greenhouse Report, Annex 2.1, Part II.

4.3.2 Swine

Swine were used in the experimental program because young adults resemble adult human subjects in weight and volume. The interaction of ionizing radiation with matter is, among other factors, a function of volume. Since swine also resemble man physiologically, it is reasonable to assume that the MLD and the curve of survival rate vs dose of initial nuclear radiations will be comparable in the two species when individuals of similar weight and volume are studied. Swine were used in Operation Crossroads and were found to be suitable animals for a field test. Their response to X rays of 1,000 and 2,000 KVP has been studied at the Naval Medical Research Institute and at the Naval Radiological Defense Laboratory. Histopathological preparations of swine exposed during Operation Crossroads and to supervoltage X rays are quite similar to each other and to tissues obtained from Japanese casualties.[3] Landrace swine have been used in the radiation experiments performed at the Naval Medical Research Institute, and this was the strain selected for Operation Greenhouse. The animals were procured from the United States Department of Agriculture Experimental Station, Beltsville, Maryland. They were shipped to the animal holding colony at the Naval Radiological Defense Laboratory. The veterinarian of Task Unit 3.1.2 cared for them there until July 1950, when they were sent by sealift to Eniwetok aboard the *USS Warwick*. The sows were bred after arrival on Japtan.

For the studies of thermal injury, young Chester White pigs were used. The nonpigmented skin of these animals closely resembles human skin, not only in architecture, but also in response to thermal injury.[4] Sows and boars of this strain were obtained from the same breeder who supplied the pigs for the control studies at the University of Rochester

[3] The material in this section was derived from published reports of the Director of Ship Material, Bureau of Medicine and Surgery Research Group, U. S. Navy, and from personal communications from members of the Group.

[4] Greenhouse Report, Annex 2.2, Part IX.

College of Medicine and Dentistry. The Chester White stock was transferred to Eniwetok in the same way and at the same time as the Landrace stock.

4.3.3 Dogs

Dogs are excellent animals for use in experimental medicine. They are generally available and are easy to handle. The circulatory system, the endocrine system, the general metabolism, hematopoiesis, and the mechanism of the coagulation of blood of the dog closely resemble these features in man. Dogs have been used extensively to study radiation sickness resulting from exposure to X rays. For Operation Greenhouse, the Walker strain of the American foxhound was selected. This strain is fairly homogeneous, and it was possible to obtain large numbers of them in rural communities in southeastern United States. The breeding stock was purchased in Tennessee and shipped to the animal holding colony at the Naval Radiological Defense Laboratory. The healthiest animals were selected from the original group and transferred by sealift on the *USS Warwick* to Japtan in July 1950. Breeding was started after the animals were acclimatized and had recovered from disorders that developed during the trip. The animals bred slowly at first and it was necessary to import additional breeders. Since there were not sufficient Japtan-born dogs of suitable size at shot time, some of the breeding stock was used in the experimentation.

4.3.4 *Tradescantia*

Tradescantia, the common spiderwort, has been used extensively in studies of the mode of action of ionizing radiation on living cells.[5,6] The microspores of the budding flowers contain six large chromosomes in which structural and physiological alterations due to radiation can be seen easily. The yield of structural changes is dependent on the dose of radiation, and the relationship is sufficiently reliable to justify the use of *Tradescantia* as a biological dosimeter. The response of *Tradescantia* chromosomes to X rays and gamma rays is independent of energy over a wide range and is also independent of intensity over the range of dose rates likely to occur with a nuclear explosion. The scoring of the structural changes due to radiation is comparatively simple, and the results of relating yield to dose are reliable in the range of 25 to 500 rep. It is possible, using *Tradescantia,* to estimate the neutron flux in a mixed radiation such as the initial nuclear radiations of an atomic bomb. The special characteristics that have been mentioned were the reason for the inclusion of *Tradescantia* in the protocol.

4.3.5 Corn Seed

Corn was exposed to high intensities of the initial nuclear radiations in Operations Crossroads and Sandstone. When this material was grown, unusual somatic mutations were observed which were manifested as bizarre changes in the pigmentation of the primary leaves.[7] The estimated dose of gamma rays which the corn seed received was of the order of 5×10^3 to 3×10^5 r. It has not been possible, to date, to reproduce these effects with equivalent doses of X ray. Because of the unusual results obtained with corn exposed in the other weapons tests, George W. Beadle, California Institute of Technology, wished to have more irradiated corn for genetic study.

4.3.6 *Glomerella*

Specimens of *Neurospora crassis* were exposed to initial and residual nuclear radiations at Operations Crossroads and Sandstone, and a large yield of genetic and biochemical mutations were obtained, the study of which is still in progress. Valuable insight into the nature of fundamental biochemical processes is being gained from the study of such mutations. The mould *Glomerella* resembles *Neurospora* in its response to large doses of radiation and a good yield of mutations is produced. The high dose rate possible with an atomic explosion is particularly useful in the production

[5] D. M. Lea, *Action of Ionizing Radiation on Living Cells* (Cambridge, 1946).

[6] Greenhouse Report, Annex 2.2, Part IV.

[7] Appendixes 9 (1949) and 10 (1950) to the Final Report, Operations Crossroads, Joint Task Force One.

of mutations in such material. At the request of George W. Beadle *Glomerella* was included in the protocol of the biomedical program.

4.3.7 Summary

At the first meeting of the ad hoc committee, it was agreed that the biological experimentation should be restricted to four species: mice, swine, dogs, and *Tradescantia.* Each of these species has been used in radiobiological research for many years. Two of them, mice and *Tradescantia,* have been studied so exhaustively with quantitative techniques that it is appropriate to consider them "calibrated" species in the same sense that one speaks of a calibrated instrument. It is proper to consider that certain valid parameters of the biological effect of radiation can be determined, such as the MLD and the per cent change in weight of the spleen and thymus of mice, or the yield of chromosome and chromatid aberrations in *Tradescantia.* It is probably correct to infer, with some reservations, that the same quantity of ionization in the tissues will produce the same change in such parameters regardless of the source or characteristics of the radiation which is used. The extent to which radiations of varying characteristics produce ionization in tissue is difficult to determine except in terms of the biological effects which occur. Physical measurements of radiation are usually related to the ionization produced in air, the composition of which is more homogeneous and better known than that of tissue. The relationship between similar biological effects resulting from different quantities of radiation of varying characteristics is usually described as the RBE of the various radiations. In the case of the initial nuclear radiations of an atomic bomb, there was no information on its RBE, prior to the experimentation with these calibrated species in Operation Greenhouse.

Swine and dogs are not calibrated species in the sense that the term is applied to mice and *Tradescantia.* It is possible, however, by following rigorously controlled experimental methods, to use these species in such a way that valid information can be obtained on the biological effect of initial nuclear radiations in large mammals. The special conditions that had to be fulfilled were the provision of animals as nearly alike as possible with respect to age, weight, physiological condition, and freedom from disease. In the case of the large mammals, a primary objective of the experimentation was to study survival as a function of distance. The fiducial limits of the parameter, distance, could be no less than 95 per cent [8] if the data were to be useful for planning the medical care of victims of atomic warfare. It was theoretically possible to attain such a fiducial limit in suitable animals, properly prepared and selected for the experiment.

4.4 DESIGN OF THE EXPERIMENTS

4.4.1 Introduction

When the protocol of the biomedical program was drawn up by the ad hoc committee, it was recommended that the effects of the field variables: nuclear radiation, thermal radiation, and blast, should be studied separately. To accomplish this it was necessary to design "exposure equipment" which would permit the isolation of the variable under investigation. At the same time it was necessary that the equipment should provide environmental conditions for the biological specimens such that the experiment would not be compromised by excessive heat, lack of oxygen, accumulation of carbon dioxide, or excessive humidity. The locations of the exposure equipment, the stations, were determined accurately by the surveyors of the contractor. This was necessary since all the biological effects were expressed as functions of distance as the first step in their interpretation of the results. The final steps in the determination of the biological parameters of the field variables were accomplished in one of two ways: (1) by comparison with the control data, in which case the biological effect obtained in the field was expressed as equivalent to that produced in the laboratory by any given dose,

[8] This fiducial requirement was based on the assumption that the MLD would be delivered at about 1,500 yd.

or (2) by correlation with physical measurements of Programs 1 and 2, in which case the magnitude of the biological effect as a function of dose was obtained.

4.4.2 Exposure Equipment

Detailed descriptions of the apparatus designed for the exposure of biological specimens are given in the appropriate annexes.[9-13] Summary descriptions of the seven types of units that were used follows:

1. Cylinders, Fig 4.1: These exposure units were pressure-resisting cylinders 48 in. long and 26 in. ID, fabricated from aluminum alloy $\frac{3}{16}$ in. thick. The ends of the cylinder were closed by aluminum castings bolted to a welded flange. The castings supported ventilating fans and a poppet-valve mechanism which completely closed the cylinder on signal and opened automatically a few minutes later. Single pressure cylinders bolted to sturdy legs imbedded in individual reinforced-concrete slabs were used for the series 70, 71, 72, and 83 stations and contained the specimens listed in Table 4.1. All cylinders were oriented with their long axis perpendicular to a radius of the tower. For Easy Shot the closest cylinder was 900 yd from zero. None of the units were deformed or displaced by the blast, and only 2 of the 238 placed on Engebi were damaged by flying missiles. An insulated liner fitted snugly inside the cylinder. It consisted of two cylinders of aluminum $\frac{1}{16}$ in. thick, separated by plywood spacers 1 in. thick. The space between the inner and outer walls was filled with vermiculite. The liner, in addition to providing thermal insulation, was used to transport biological specimens from the laboratory to the test site. The environmental conditions within the insulated cylinder units were adequate for dogs. Mice and swine, however, required more ventilation, and lost approximately 10 to 20 per cent of their body weight during the 24- to 30-hr period of confinement. The attenuation of gamma rays was studied using 1 curie of radium, 9 ft from the cylinder, and was found to be approximately 10 per cent.

TABLE 4.1 LIST OF SPECIMENS PLACED IN CYLINDERS

STATION NO.	TYPE OF SPECIMEN	PROJECT NO.
70,71	Mice for determination of MLD	2.4.1.1
	Mice for study of survivors	2.5.1.1
	Mice as biological dosimeters	2.5.5.4
	Tradescantia as biological dosimeters	2.5.5.1
	Mouse phantoms	2.4.4
	Film packs	1.2.4
	Pressure-temperature recorders	2.3
72	Swine for determination of MLD	2.4.1.4
	Dogs for determination of MLD	2.4.1.5
	Swine phantoms	2.4.4
	Film packs	1.2.4
	Ground radiac equipment	5.1
	Pressure-temperature recorders	2.3
83	Swine for serial pathology	2.4.1.2
	Dogs for serial pathology	2.4.1.3
	Film packs	1.2.4
	Pressure-temperature recorders	2.3
80	Swine phantoms	2.4.4
	Pressure-temperature recorders	2.3

2. Hemispheres, Fig. 4.2: These units consisted of aluminum cylinders placed vertically in the ground with a hemispherical dome secured to the upper end. The cylindrical portion of the unit contained a fan to circulate air, and the large volume of the cylinder below ground acted as a heat exchanger. The air-intake and exhaust pipes were fitted with poppet valves that closed on signal and reopened automatically 1 min later. Three types of hemispherical domes were used: aluminum, ¼ in. thick; lead, 7 in. thick; and lead sheathed with $\frac{1}{32}$ in. of cadmium. The material exposed in the hemispheres is listed in Table 4.2. Mice were placed in lucite cages supported inside the unit about 9 in. above the ground line. The environmental conditions within the hemispheres were adequate for the mice, and the weight loss during the period of transportation and confinement was insignificant. Hemisphere units with aluminum domes were located as close to zero as 1,260 yd for Easy Shot. Units with lead domes were placed as close as 675 yd for Easy Shot, and 1,000 yd for George Shot. None of the units

[9] Greenhouse Report, Annex 2.3.
[10] Greenhouse Report, Annex 2.4, Part II.
[11] Greenhouse Report, Annex 2.7.
[12] Greenhouse Report, Annex 2.9.
[13] Greenhouse Report, Annex 2.4, Part I, Section 3.

TABLE 4.2 LIST OF SPECIMENS PLACED IN HEMISPHERES

STATION NO.	TYPE OF SPECIMEN	PROJECT NO.
73[a]	Mice as biological dosimeters	2.5.5.5
	Tradescantia as biological dosimeters	2.5.5.1
	Film packs	1.2.4
	Neutron threshold detectors	1.5.2.1.1
	Pressure-temperature recorders	2.3
	Mice for study of cataracts	2.5.1.2
85[a]	*Tradescantia* as biological dosimeters	2.5.5.1
	Neutron threshold detectors	1.5.2.1.1
	Film packs	1.2.4
74[b]	Mice as biological dosimeters	2.5.5.4
	Tradescantia as biological dosimeters	2.5.5.1
	Film packs	1.2.4
	Ionization chambers	2.4.4
	Pressure-temperature recorders	2.3
510 series	Ground radiac equipment	5.1
5110 series	*Tradescantia* as biological dosimeters	2.5.5.1

[a] These units had lead domes.
[b] These units had aluminum domes.

were deformed or damaged by blast, none of the electrical circuits failed, and all the animals placed in them were recovered alive.

3. Thermal stations, Fig. 4.3: The animals used for the study of thermal burns were placed in blockhouses of concrete or wood sufficiently strong to withstand the blast. It was not possible to provide a simple reliable method of exposing a portion of the animal's skin to thermal radiation without permitting some exposure to gamma rays. At the closest thermal station, No. 75, the dose of gamma radiation was a lethal one, and at all the more distant stations it was inconsequential. The animals used for the burn study had to be anesthetized so that no reflex or spontaneous movement would occur at the time of burning. The burns that were produced for study were small in area, and they were inflicted through windows in the shelter against which the flank of the animal was securely placed. The combination of anesthesia and compression of the animal to assure correct positioning produced a definite hazard of respiratory insufficiency, and the death of some of the animals was inevitable. Adequate ventilation of the shelters was provided by electric fans. The special devices for the study of the time and spectral dependency of the flash burn are described in detail in the project report.[14]

4. Standpipes, Fig. 4.4: This unit consisted of a section of galvanized iron pipe 30 in. long, and 6 in. ID. It protruded from the ground at an angle of 45° from the tower, and the lower portion was enclosed in a block of concrete, leaving the lower opening clear to facilitate recovery of specimens in the event the cap was damaged. The upper end was closed with a screw cap. These units were used for the exposure of corn seed, *Glomerella,* and Vycor glass to very high doses of nuclear radiation. The biological specimens were protected from the effect of solar radiation by adequate insulation with fiber glass.

5. Foxholes, Fig. 4.5: Each foxhole was a trench 4 ft deep, 6 ft long, and 3 ft wide, the walls and floor of which were shored with ½-in. plywood. A wire mesh, placed at an angle in the trench, confined the dogs to the floor of the hole and to the portion of it toward the tower. A water supply and various instruments were placed within the enclosure. The arrangement of the mesh was such that

[14] Greenhouse Report, Annex 2.2, Part IX; and Greenhouse Report, Annex 2.7.

TABLE 4.3 LIST OF SPECIMENS PLACED IN STANDPIPES

STATION NO.	TYPE OF SPECIMEN	PROJECT NO.
84	Corn seed	2.5.5.2
	Glomerella	2.5.6
	Vycor glass	2.5.7
	Film packs	1.2.4
	Pressure-temperature recorders	2.3

TABLE 4.4 LIST OF SPECIMENS IN THERMAL STATIONS

STATION NO.	TYPE OF SPECIMEN	PROJECT NO.
75 to 79	Swine for burn study	2.4.2
	Dogs for burn study	2.4.2
	Samples of QM clothing	2.4.2
	Bolometers	2.4.2
	Film packs	1.2.4
	Pressure-temperature recorders	2.3

TABLE 4.5 LIST OF SPECIMENS IN DRONE AIRCRAFT

TYPE OF SPECIMEN	PROJECT NO.
Mice as biological dosimeters	2.5.5.4
Tradescantia as biological dosimeters	2.5.5.1
Mice for study of fission products	2.5.4
Film packs	1.2.4
Neutron threshold detectors	1.5.2.1.1

none of the dogs were exposed to the thermal radiation from the fireball.

6. Units in B–17 drone aircraft, Fig. 4.6: The mice that were carried in the drone aircraft were placed in cages in two sorts of compartments in the outer wall of the fuselage. One compartment was ventilated by filtered air from which fission products were removed. The other compartment was equipped with tubes which permitted the entrance of air containing fission products during the plane's passage through the cloud. The rate of air flow was regulated by means of valves, and identical conditions of ventilation were produced in the cages in each of the three drones.

TABLE 4.6 LIST OF SPECIMENS IN FOXHOLES

STATION NO.	TYPE OF SPECIMEN	PROJECT NO.
86	Dogs for blast study	2.4.5
	Film packs	1.2.4
	Neutron threshold detectors	1.5.2.1.1
	Pressure-temperature recorders	2.3

7. Phantoms, Fig. 4.7: The phantoms were of two types. One consisted of a series of seven hollow lucite spheres, the wall thickness of which varied from 0.5 to 17.5 cm. These were suspended from A-frames by heavy steel tackle and contained ionization chambers, phosphor dosimeters, and film. The other phantoms simulated mice and swine, respectively, and were constructed of layers of masonite, each ¼ in. thick. Film packs were distributed throughout the swine phantom in a known geometrical pattern and in such fashion that the depth dose and the distribution of the dose could be determined. The mouse phantom was a three-layer masonite "sandwich" containing two film packs. The masonite phantoms were placed within cylinders and hemispheres in the same geometry as the experimental animals.

The biomedical experimentation was cooperative in character, and most of the stations contained specimens which pertained to more than one project. In this way it was possible to obtain correlation with physical measurements made in the same geometry and to make intercomparisons of the results of several biomedical experiments. The variety of material placed in each type of exposure equipment, and the projects to which they belonged, are listed in Tables 4.1 to 4.6, respectively. Not every station of a given type (for example, the hemisphere stations) contained all the kinds of specimens listed in the table, but the material was distributed according to plan to provide the best information possible.

4.4.3 Location of the Stations

The term "station" was used to describe the position at which exposure equipment was placed to obtain a measurement. In most cases, a single unit occupied a station. In the case of the double cylinders for the large animals, the station consisted of 8 units (No. 72i), 9 units (Nos. 72a to h inclusive), or 24 units (Station 83). The surveyed distance from zero to these multiple-unit stations was measured at the geometrical center of the group of units. The positions of all the stations of Program 2 with respect to zero for each shot are given in Tables 3.1 to 3.7 inclusive. These tables include the expected doses of gamma rays, thermal radiation, and blast at the distances at which biological specimens were exposed. The theoretical and empirical justification for the choice of locations has been discussed in Chap. 3. Because of the uncertainty in the prediction of the yield of the weapons tested, it was necessary to place a sufficient number of stations to bracket the range of expected biological effects over the wide range of yield. Maps of the shot islands showing the positions of the stations that contained biomedical specimens are given in Figs. 4.8 to 4.13.

4.4.4 Selection of Animals

The determination of the MLD is a standard procedure in biological assay, and the manner of the selection of the animals for dose groups is an important element in the design of the experiment. When quantitative data are sought from any biological material it is important to eliminate so far as possible the introduction of systematic bias resulting from the operation of personal prejudice, and other factors, in the selection of the animals for the dose groups. The methods of selection used in Operation Greenhouse were as follows:

(*a*) *Animals for the determination of the MLD.* (1) Swine and dogs: The distribution of age, sex, and weight for all the swine and dogs in the animal colony was determined. The groups of 10 swine and 10 dogs which were placed in each of the stations of the 72 series, and the 32 swine and 32 dogs which were placed in Station 83, had the same age-weight-sex distribution as was found for the entire colony. Individual animals were assigned to each group on the basis of a table of random numbers. The nine groups, of 10 dogs and 10 swine each, were then segregated in the animal colony prior to Easy Shot. When the animals were loaded into containers for movement to the shot island, each group retained its identity, but the station to which any group was delivered depended on chance alone. Accordingly, there was an equal probability that any one animal would be placed in any one of the nine stations.

(2) Mice: Because of the large numbers of mice used (approximately 8,000), it was not possible to use a table of random numbers to assign individual mice to each of the 29 stations of the 70, 71 series. The age-weight-sex distribution was determined for the group of mice to be used. Eight age-weight categories were established for each sex, and all the mice in each category were placed in bins from which they were removed at random to form groups of 30 and 40 of each sex. Each group of 30 or 40 male or female mice had the same age-weight distribution as the entire population from which it was selected. Each of the stations of the 70, 71 series contained some integral multiple of 30 and 40 mice of each sex, and the groups were assigned to individual stations by means of a table of random numbers. Accordingly, there was an equal probability that any one mouse would be placed in any one of the 28 stations.

(*b*) *Mice for biological dosimeters.* The female mice that were used for the mouse thymus-spleen system of dosimetry were selected on the basis of age and weight from the portion of the hybrid mouse colony set aside for this purpose. They were formed into groups of 30, each of which was representative of the entire experimental group with respect to the distribution of age and weight. The assignment of the groups of 30 mice to the stations of the 73 and 74 series was made by means of a table of random numbers. There was an equal probability that any one mouse would be placed in any one of the hemisphere stations.

(*c*) *Tradescantia.* *Tradescantia* were chosen from the greenhouse on the basis of an appropriate stage of development of the efflorescences. They were placed in jars in an unsystematic manner, and then assigned to the stations of the 70, 71, or the 73, 74, 85 series, or the drone aircraft, on the basis of chance alone. Since the plants were cut at the latest time possible before the test, it was not convenient to use the technique of randomization that was applied to the animals. It is unlikely, however, that a systematic bias occurred which could affect the results.

4.4.5 Analysis of the Data

The experiments that required biometrical treatment of the results were planned in consultation with qualified bio-statisticians. The planning included the design of the control studies as well as the field experiments. It was a distinct advantage to plan experiments with regard to the technique which would be used to analyze the data.

Dose-mortality studies were performed using mice, swine, and dogs. The results of these studies, as well as the results of the control studies using X rays, were submitted to an identical type of probit analysis using the same scale for dosage. The preliminary anal-

ysis of the results of the field study were carried out before the final estimate of dose as a function of yield and distance was available from Program 1. The analysis was facilitated by using a relative dosage of unity for the MLD. The relative dosages at various stations on the shot island were then calculated from Eq. 4.1, *Greenhouse Handbook*.[15] The relative dosage of X rays used in the control studies were calculated directly. This technique of analysis permitted a comparison of the slopes of the regression lines for the experimental and the control groups without regard to the actual value for dose in roentgens. After the Sievert ionization chambers, Project 2.4.4, were recalibrated, dose vs distance tables were prepared for the first three shots. The average values obtained from these ionization chambers were fitted to a line, the slope of which was determined by analysis of the mouse thymus-spleen system data. These values for dose, in roentgens measured in air, were used for preliminary interpretation of the data. When the estimate of gamma-ray dose as a function of distance, made by Program 1, become available, it will be possible to substitute it in the plots and to undertake an evaluation of the RBE on the basis of the most acceptable physical measurement.

The mouse thymus-spleen system of dosimetry was carried out with groups of mice sufficiently large to permit statistical treatment of the average value for weight loss of the organs after irradiation. The regression equation for the mean weight loss of each organ as a function of dose of X rays was used to determine a tentative equivalent value for the dose of gamma rays and neutrons. These data were also submitted to a probit analysis with some improvement in the usefulness of the regression line. This tentative value for dose multiplied by the square of the distance (to remove the spherical-geometry factor) was plotted against distance to give a regression curve which could be submitted to further analysis, and compared with similar data obtained by means of calibrated film, scintillation counters, ionization chambers, ground radiac equipment, etc., or computed from the estimates of yield supplied by Program 1. The relationship was established in this way between the curves obtained for the mice and that obtained by physical measurement. This relationship could be translated into an estimate of the RBE and of the neutron flux.

The *Tradescantia* system of biological dosimetry was submitted to a similar type of analysis.

The mice that survived longer than 28 days after exposure in the dose-mortality experiment were sent to Oak Ridge National Laboratory where they will be observed for the duration of life. IBM cards were prepared for all the mice used in this experiment, as well as for the mice in which the induction of cataract was studied. The following data were recorded: age, sex, weight at the time of exposure and every 2 to 4 weeks thereafter, position in the cylinder exposure unit, distance from zero, estimated dose, time of death, cause of death and results of autopsy examination. As the data are accumulated they will be submitted to biometrical treatment to investigate the relationship between dose and duration of life, dose and occurrence of neoplasma, dose and the time of onset of cataract, etc. Since the average life span of the LAf_1 mouse is of the order of 900 to 1,000 days, the results of this study will not be available until long after the publication of this report.

The analysis of the film used for the depth-dose measurement and for the determination of the HVL in unit-density material was carried out by standard techniques used in radiology.

4.4.6 Summary

The design of the biomedical experiments has been described. It was necessary to develop exposure equipment which would provide habitable conditions for the animals and which would also permit the effects of the field variables to be studied separately. The selection of animals for assignment to the various stations was done in such a way that systematic bias was unlikely. The techniques for the analysis of the data were considered in

[15] *Greenhouse Handbook of Nuclear Explosions, Part I, Theory* (Los Alamos Scientific Laboratory, LAB–J–2182, 1951).

advance of the tests, and the details of the experimentation were planned with the help of the biometricians. Many of the studies were complementary, and most of the stations were used for specimens belonging to several projects. In spite of the unfavorable climatic conditions and the complex nature of the program, it was possible to adhere to accepted principles of the experimental design. The technical methods employed are described in detail in the annexes which contain the final report of each project, and the results of the control studies.

4.5 OPERATIONS

4.5.1 Introduction

The term "operations" is used here to describe the actions which were necessary to transport the biomedical specimens from the laboratory island to the test sites for the four shots. The equipment and the methods used for this purpose were similar for each test. The magnitude of these operations in terms of the specimens, men, and vehicles is demonstrated in Table 4.7. It was apparent at an early stage of planning that the success of the entire experiment depended on the development of a safe and efficient method of moving the test material about. The method which was finally employed is described with respect to the special equipment used and the procedure.

4.5.2 Special Equipment

All the test materials with the exception of the lucite spherical phantoms were transported from Japtan to the test sites in the insulated, removable liners of the cylinder exposure units, which are described in Sec. 4.4.2. The typical liner was modified for various special purposes, as follows: (a) with one water container, for one pig; (b) with two water containers, for two dogs; (c) with special brackets and six trays for mice for the dose-mortality study; (d) with two shelves for cages of mice for biological dosimetry; and (e) with special brackets for one swine phantom. All the liners had hinged perforated aluminum plates for end closures, and each of them when loaded could be carried by two men. The insulation was adequate to protect the animals inside from the noonday sun if the rate of air movement through the liner was at least 500 ft/min. For the most extensive operation, Easy Shot, 270 liners were used.

The handling of the liners was facilitated by the use of special barrel pallets which held six liners in two rows of three each. The two layers of the pallet were held together by pins which permitted rapid removal of the lower row of liners. A barrel pallet with liners is shown in Fig. 4.14. The pallets were handled either by a finger lift (Fig. 4.15) or by the chain hoist on the special truck. A trained team could load (or unload) a truck with three pallets containing 18 liners in less than 5 min (Fig. 4.16).

TABLE 4.7 LOGISTIC EFFORT OF THE BIOMEDICAL PROGRAM AT SHOT TIME

SHOT	NUMBER OF PROJECTS	SITES	MICE[a]	TOTAL NUMBER OF SUBJECTS		STATIONS[b]	PERSONNEL[c]	VEHICLES	BOATS	DISTANCE[d] (miles)
				Dogs	Swine					
Dog	4	1	1,170	0	0	16	16	3	2	8
Easy	16	5	11,390	164	178	173	85	7	7	18
George	8	4	1,230	0	22	60	46	5	4	12
Item	2	1	0	16	0	8	15	2	1	18
TOTALS			13,790	180	200	257				

[a] Includes the necessary controls.
[b] Actual number of structures in which material was placed on shot islands.
[c] Includes the monitors assigned for the Operation from Task Unit 3.1.5.
[d] The distance listed is that between Japtan and the most distant island on which specimens were placed.

Cab-over-engine, four-wheel-drive trucks were used to move the pallets. These trucks were equipped with an overhead frame and a monorail for a chain hoist. The bed of the truck was sufficiently long to accommodate three barrel pallets, and the loaded truck could be carried in a landing craft of the type designated "LCM" (Fig. 4.17). Three such trucks were used in the operations, and each was equipped with a two-way radio for communication with the command post and the boats.

The majority of the loaded pallets were transported to and from the test sites in the hold of landing craft of the type designated "LSU". Two of these ships were required for the Easy operation, and one for Dog and George. For Item, an LCM was adequate. The technique of loading animals, etc., into the liners and loading the pallets on the trucks was practiced repeatedly until all hands were trained in the safe and rapid handling of the equipment.

The mice and *Tradescantia* designated for exposure in the drone aircraft were transported to and from the airfield on Eniwetok by helicopter. No special equipment was required for this purpose. The containers for mice in the fuselage of the plane were removed with suitable radiological safety precautions.

4.5.3 Procedure

The plans for the movement of the experimental material from the laboratory island to the test sites were worked out in detail. Specific responsibilities were assigned to the supervisory personnel, and specific duties were posted for all hands. The loading of trucks and boats and the order of movement of every item were worked out in advance. Two dry runs were held for each of the first three shots, and the time studies performed then made it possible to prepare an accurate schedule of events for the day minus 1 and the day of the shot. The radiological safety monitors assigned to Program 2 participated in all the drills and dry runs and were most helpful in planning the recovery of specimens from stations where significant radioactive contamination was expected. Two-way radiotelephone communication was established between the boats, the trucks, the command post on Japtan, and the command boat. The net control was located in the command boat, and all activities and problems were reported to this control point and regulated from it.

As a result of the careful planning and the repeated drills, it was possible to move the experimental material for each shot with no injury to any of the personnel and no damage to any of the specimens. After the shots, recovery of specimens was accomplished on the same day and without significant radiological exposure of the personnel. The maximum permissible dose, approved by the Commander, Joint Task Force Three, was 3.0 r, and this dose was not exceeded by anyone attached to Program 2. Actually the majority of the personnel received less than 1.0 r after any shot.

A field study of this kind obviously confronts the experimenter with many problems that never occur in ordinary laboratory practice. The operations associated with Dog, Easy, and Item Shots were carried out on days when weather conditions were ideal, with the exception of the intense tropical sun. During George Shot operations the weather was bad, with rain, rough water in the lagoon, and a heavy surf on the landing beaches. Skillful handling of the boats and trucks prevented loss of specimens and injury to personnel, but the foul weather undoubtedly contributed to the death of some of the anesthetized swine. The operational requirements in the field place a limit on the type of experiment that can be conducted and the type of specimens that can be used. Material or equipment which is sensitive to adverse climatic conditions is obviously unsuitable for field use. Most ordinary laboratory procedures can be carried out in the tropics, but techniques that require low-temperature rooms, cooling of apparatus, etc., would be expensive to set up, if not impossible to operate.

4.6 CONTROL STUDIES

An extensive series of control studies were conducted as a part of Program 2. Virtually all such experiments were designed in the same manner as the field studies. In addition to

providing reliable data on the effects of radiation for comparison with the results obtained in the field, the control studies were useful for evaluating the influence of such extraneous factors as the effects of high temperature and humidity, and confinement in the exposure equipment. In the case of the mice, a 250-KVP X-ray machine was taken to Japtan to calibrate the response of the LAf_1 mice that had been raised there (Fig. 4.18). As a result of these studies, it appeared that the tropical environment alone had little influence on the reaction of these animals to ionizing radiation. Detailed reports of the control studies will be found in the Greenhouse Report, Annex 2.2.

4.7 SUMMARY

The description of the procedure for the biomedical program has been given in some detail principally for the benefit of experimenters who may be required to plan comparable studies in the future. The detonation of a nuclear weapon offers a unique opportunity to conduct an unusual pharmacological or toxicological experiment. The dose is delivered simultaneously to all the subjects, and the gradation of dose is dependent upon distance which can be measured with great accuracy. Under these circumstances variation in the results is almost entirely a consequence of the inherent biological variability of the subjects. Because of the intensity of the source, the number of subjects which can be exposed or treated at one time is limited only by the facilities for handling them. It is proper to anticipate a degree of consistency in the data which is unusual in ordinary biological assay. This fact, alone, imposes on the investigator the responsibility for scrupulous treatment of his data, not only with respect to the initial design of the experiment but also with respect to the analysis of the results. Unfortunately, nuclear weapons must be tested in uninhabited regions, and the laboratory facilities must be located many miles from the site of the explosion. When serious attention is directed to these problems, it is proper to anticipate good results. The laboratory and the animal colony for Operation Greenhouse were well equipped, and it was possible to conduct the limited experimentation with the same degree of accuracy as would be possible in the United States. The additional effort and expense required to conduct the biomedical program at Eniwetok were justified by the results. It would be regrettable if future biological studies associated with weapons tests were carried out in a less painstaking manner simply because of the apparent difficulties involved.

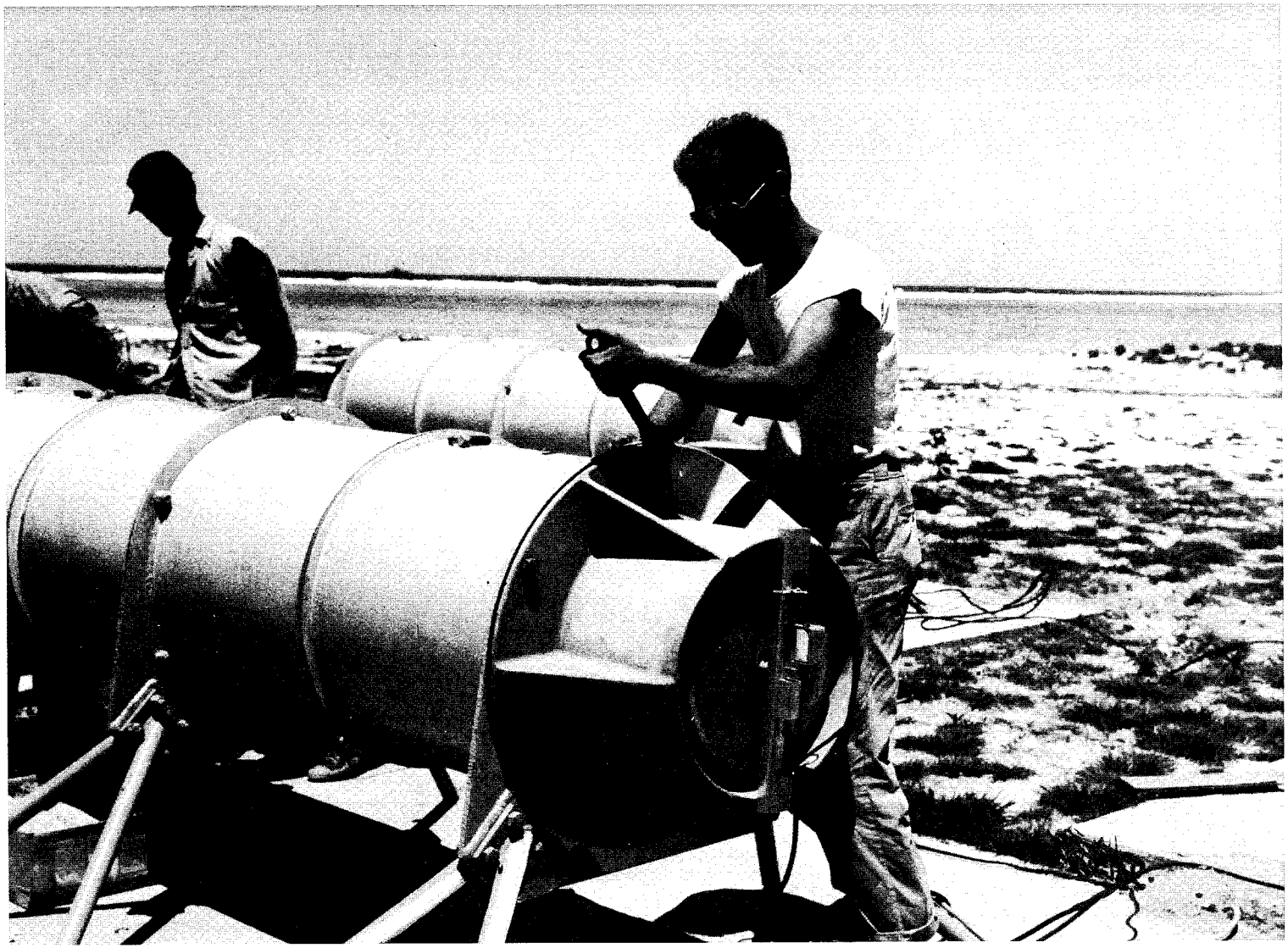
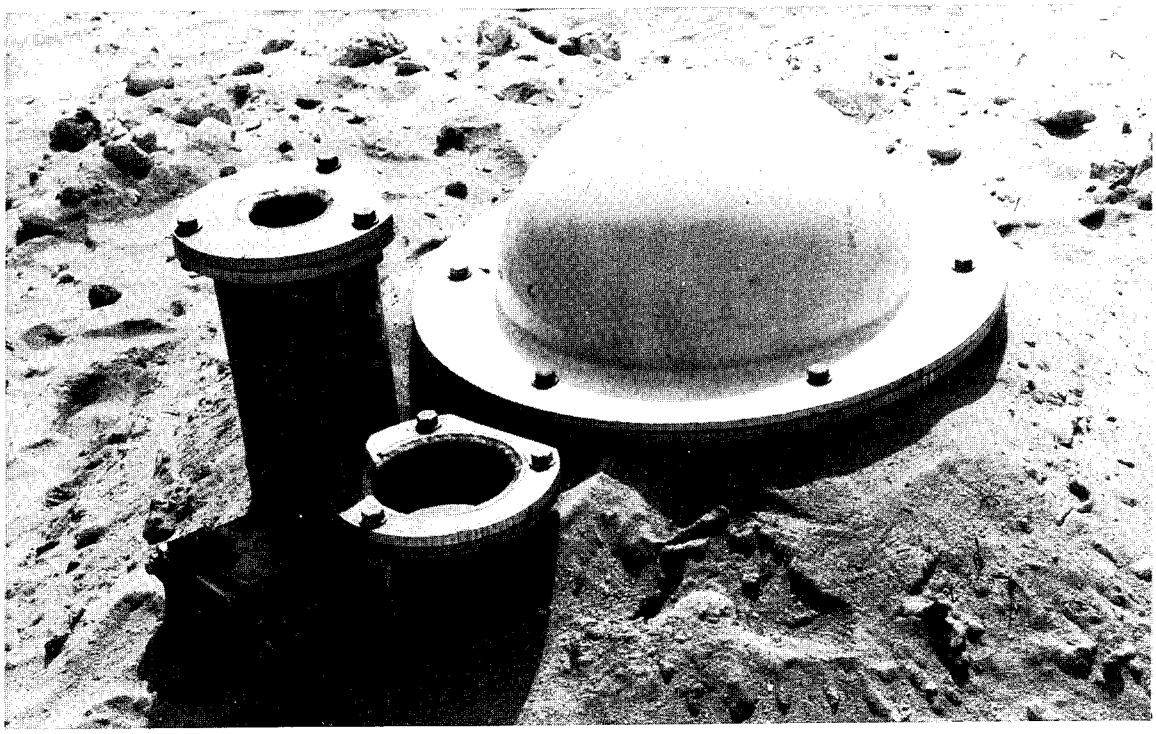


FIG. 4.1 Double, Cylinder-type Exposure Unit Installed on Site E. The workman is bolting on the casting that supports the poppet-valve mechanism, and the ventilating fans.



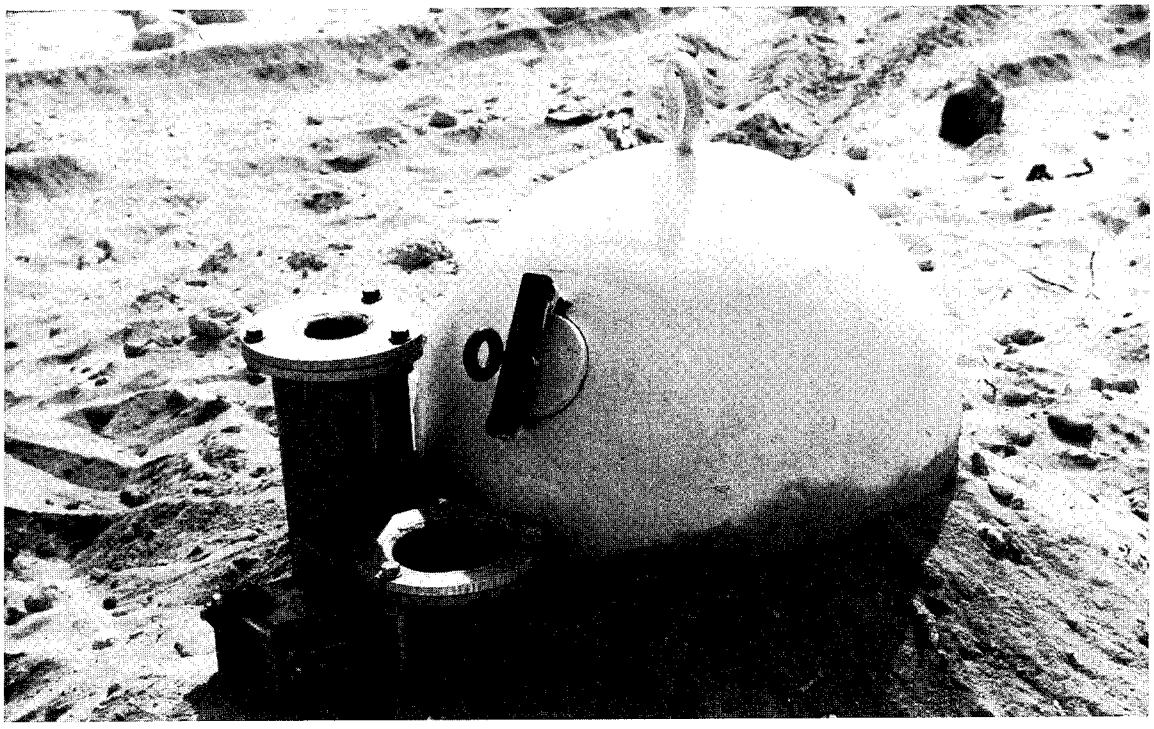


FIG. 4.2 Hemisphere Units, Ready for Use. The top shows the unit with an aluminum dome. Access to the mouse trays is accomplished by removing the entire dome. The bottom shows the unit with a cast lead dome. Access to the interior is gained through the porthole just above the air exhaust. The longer of the two vertical pipes is the air inlet, the shorter is the exhaust.

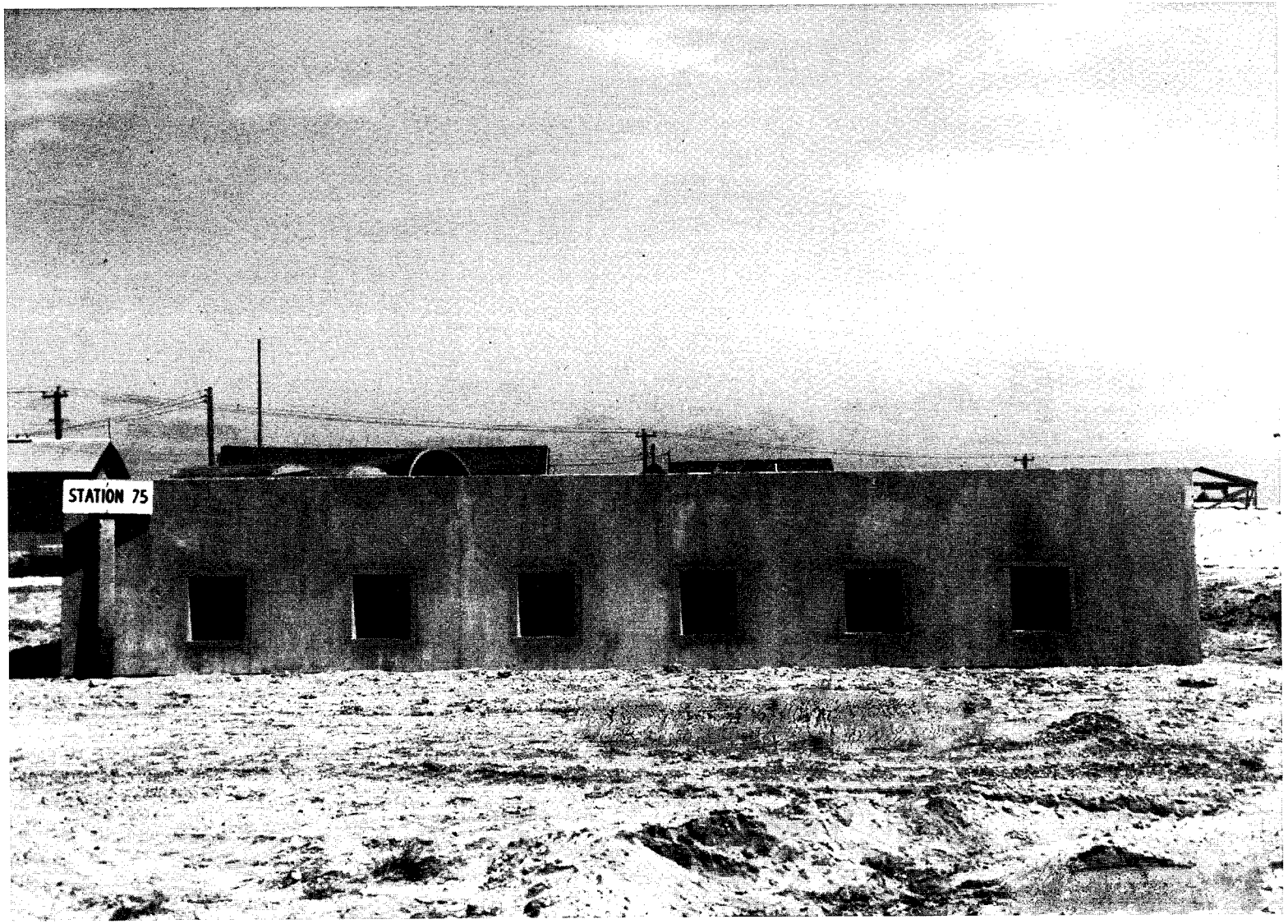


FIG. 4.3 Thermal Station No. 75, 1,375 yd from Zero on Site E. Two animals can be exposed to thermal radiation behind each of the six windows in the forward wall.

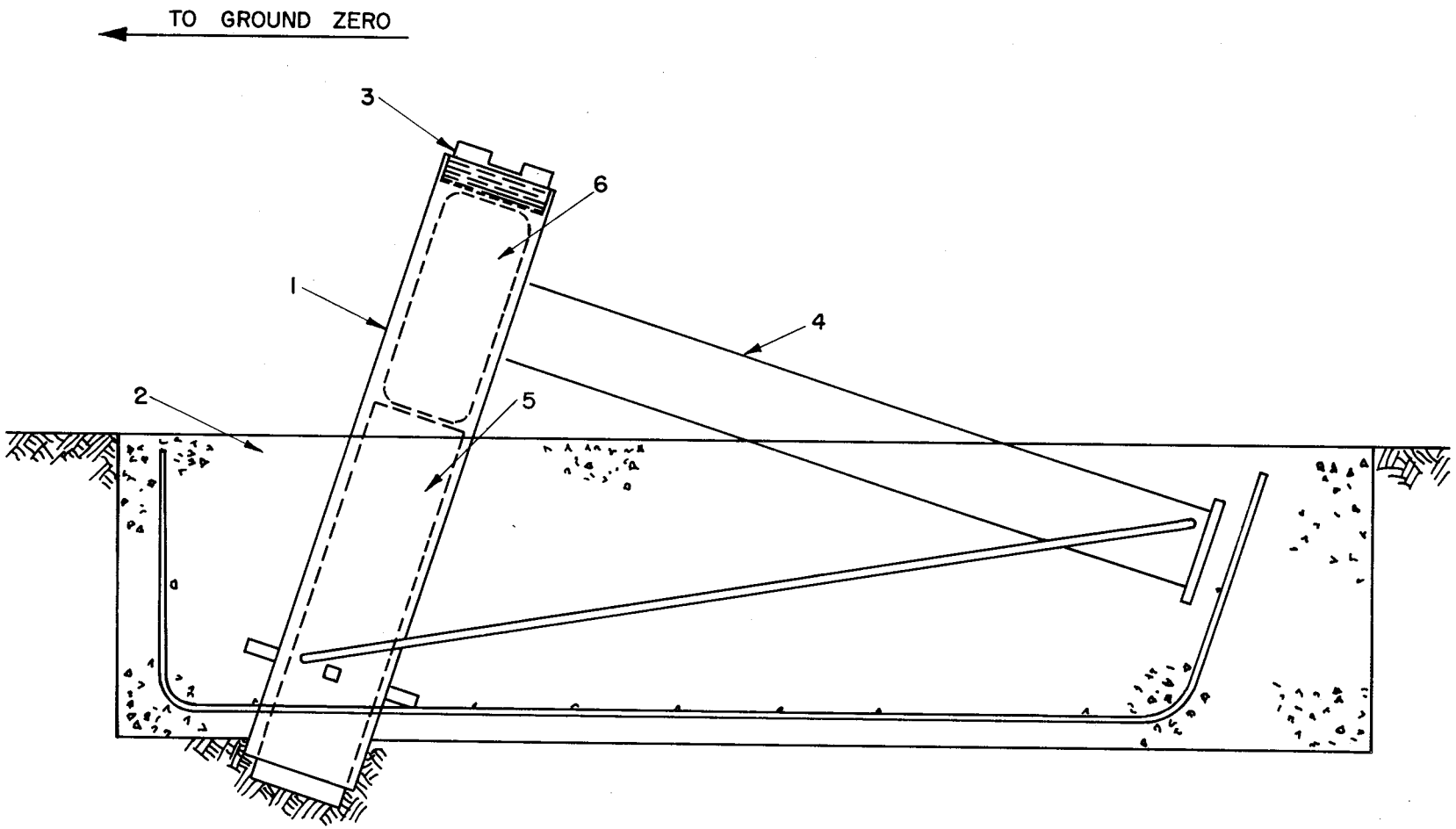


FIG. 4.4 Design of Standpipe Station. (1) 6-in.-diameter extra-strong (0.437-in. wall thickness) steel pipe, 36 in. long, firmly imbedded in a concrete footing (2). (3) Threaded steel plug. (4) 4-in. steel-pipe bracing. (5) 4- by 4-in. wooden support. (6) Test materials.

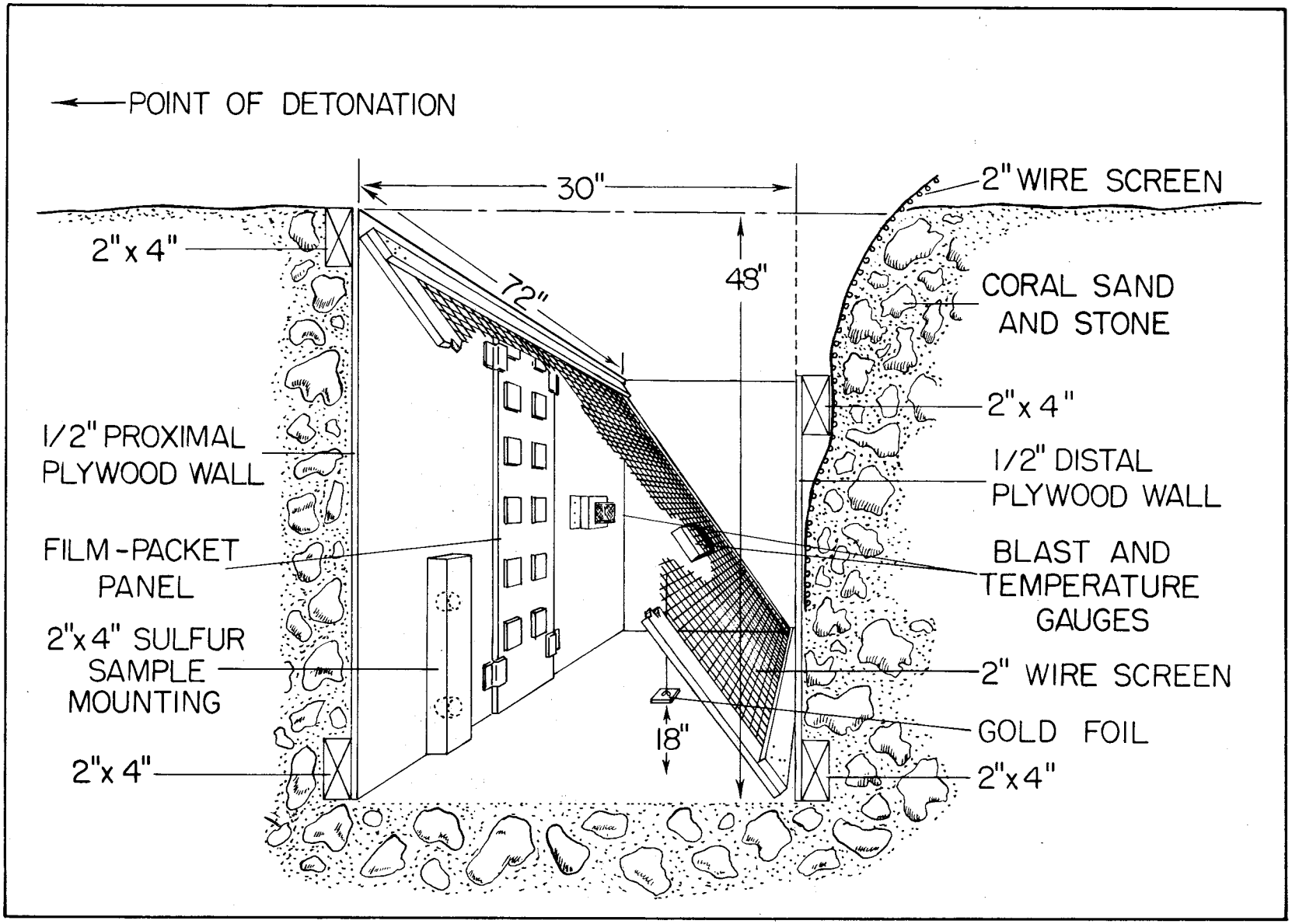


FIG. 4.5 Foxhole

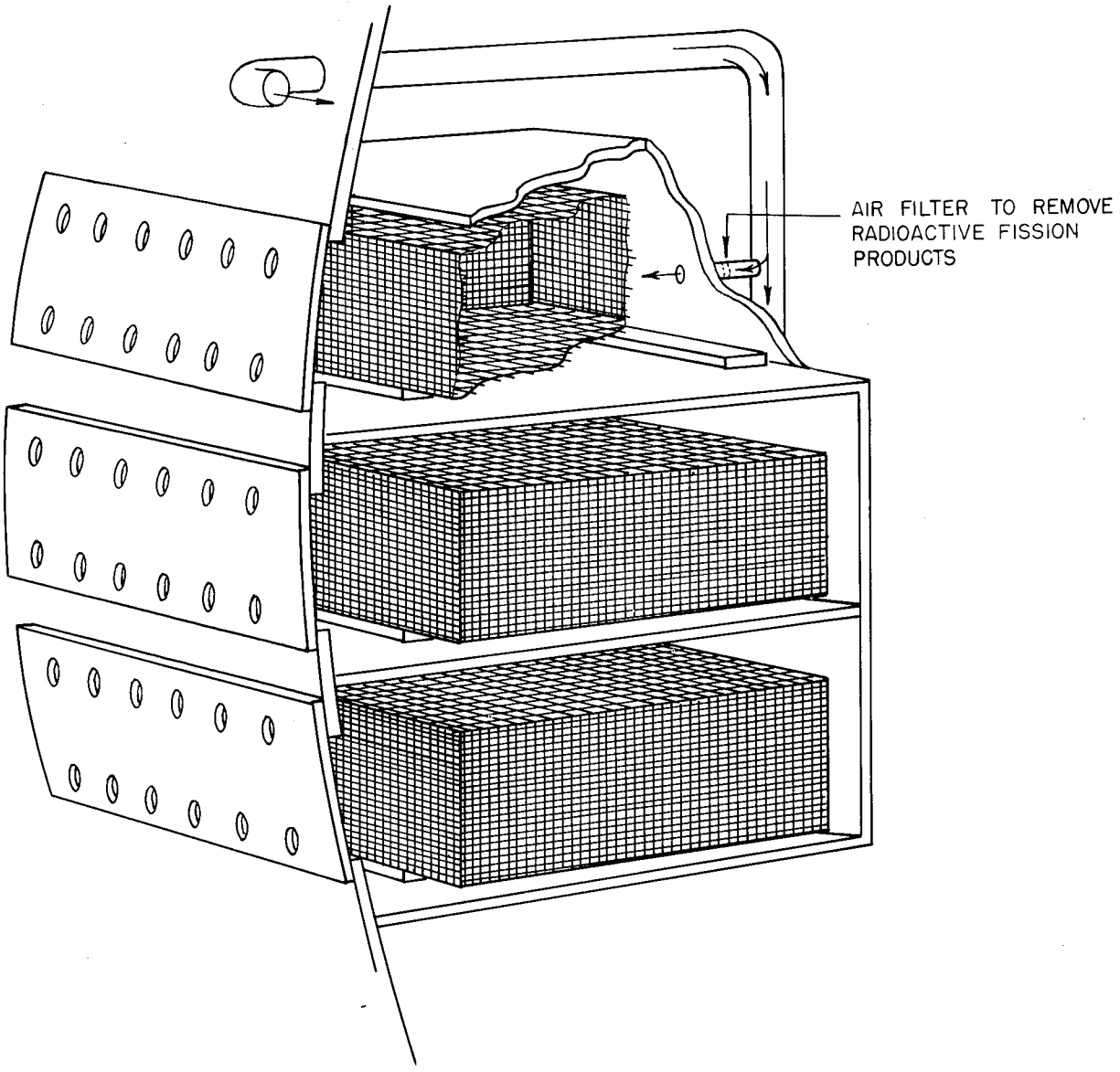


FIG. 4.6 Unit for B–17

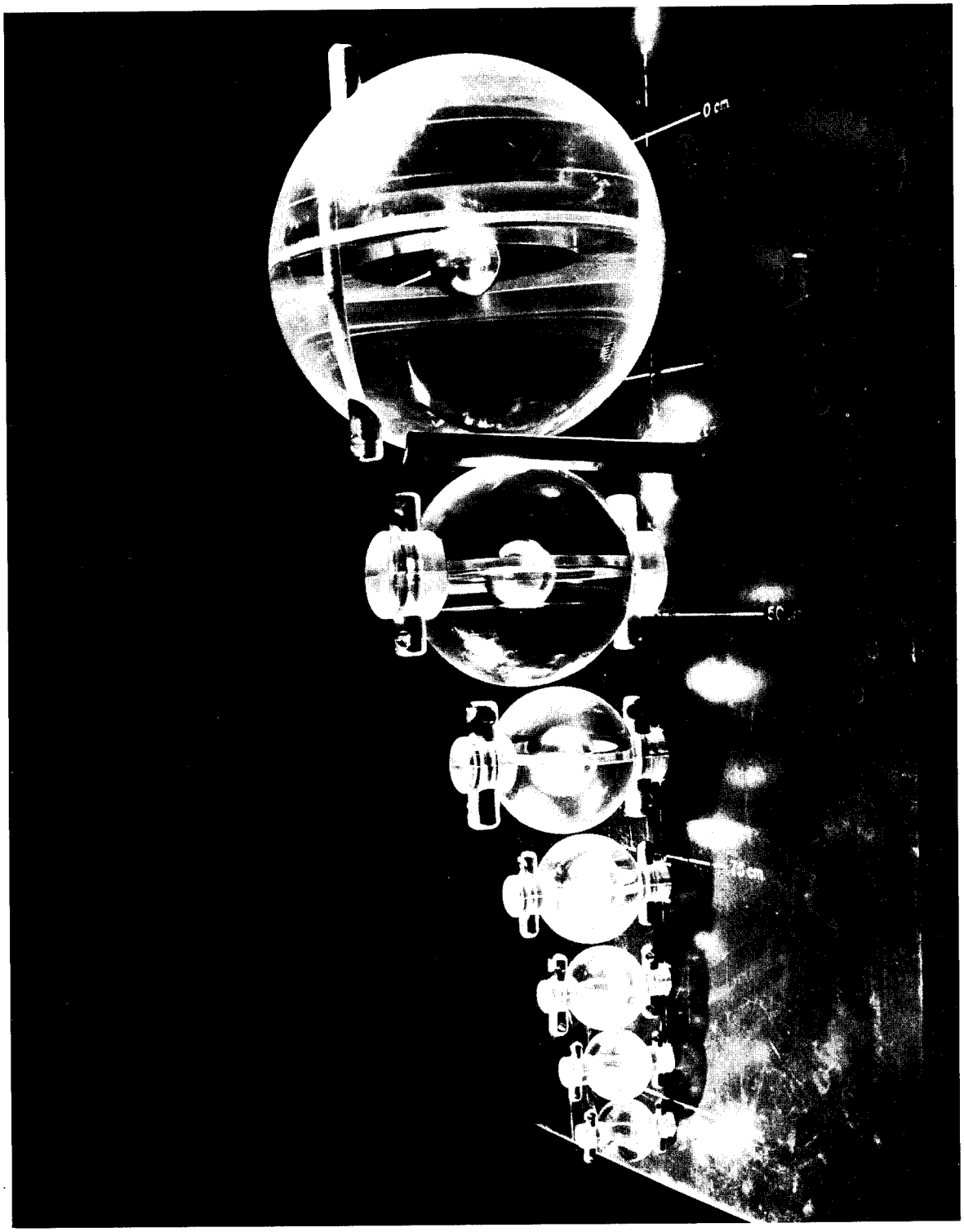


FIG. 4.7 Phantoms

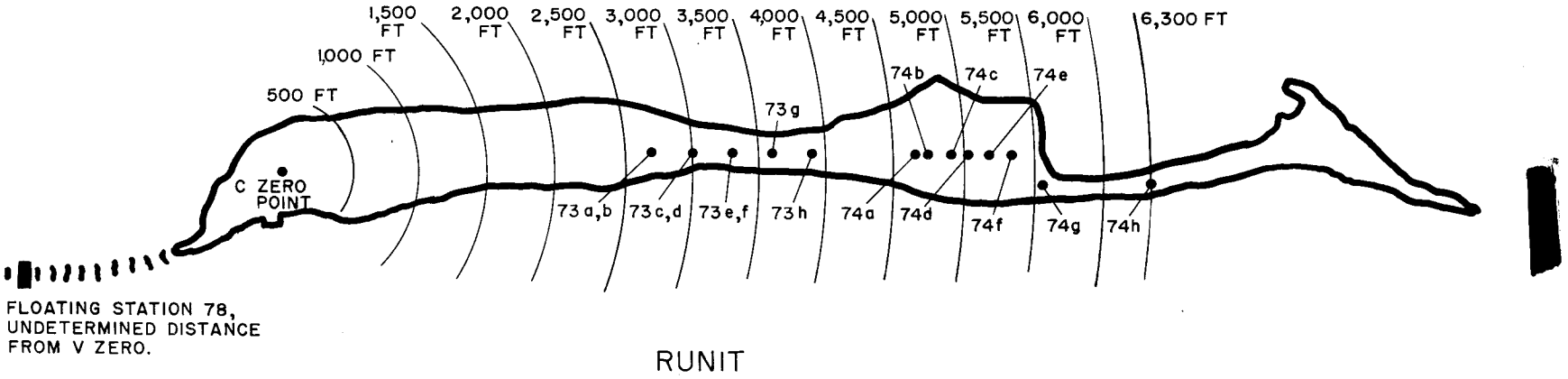


FIG. 4.8 Map of Runit, Dog Shot

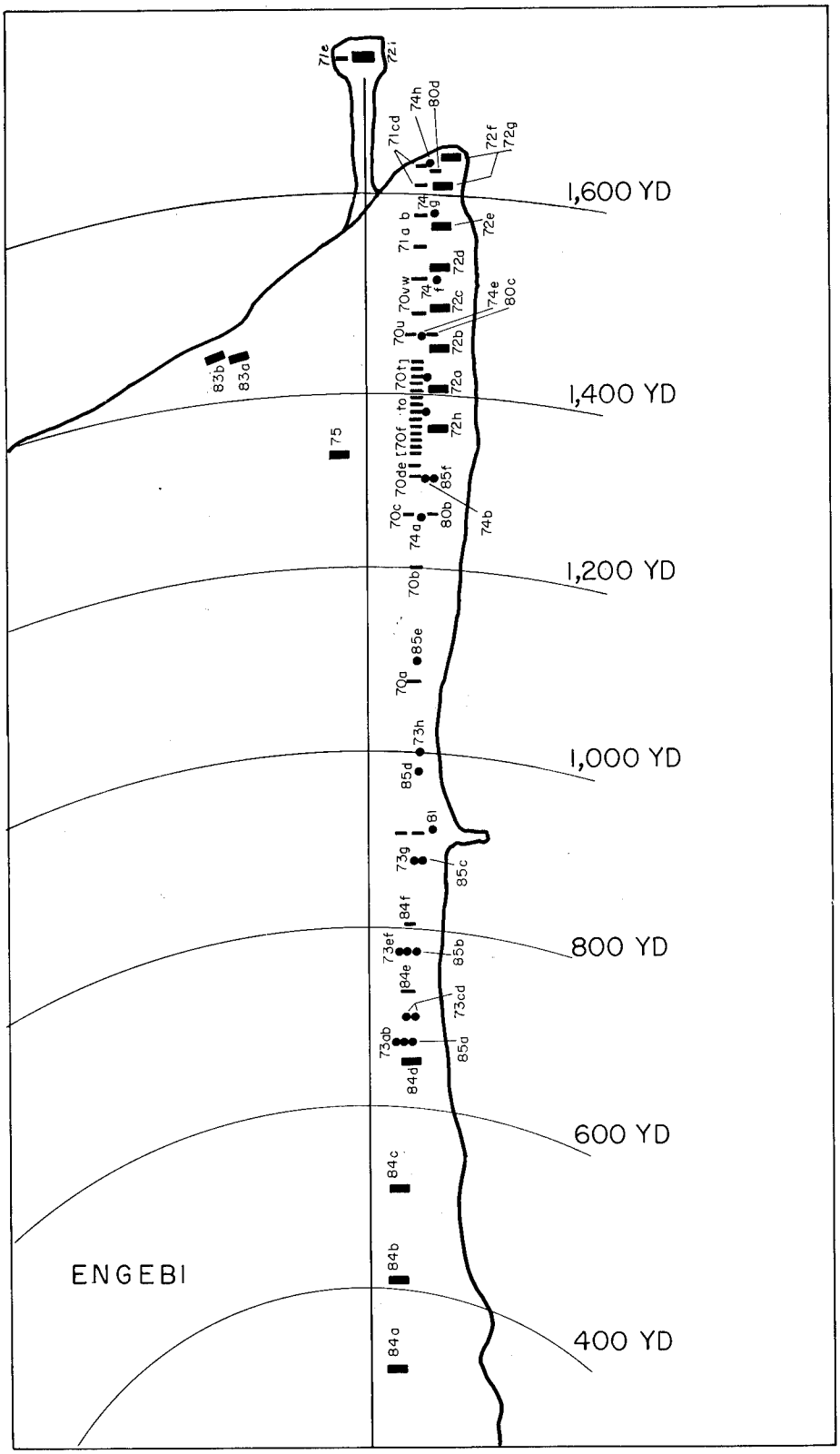


FIG. 4.9 Map of Engebi, Easy Shot

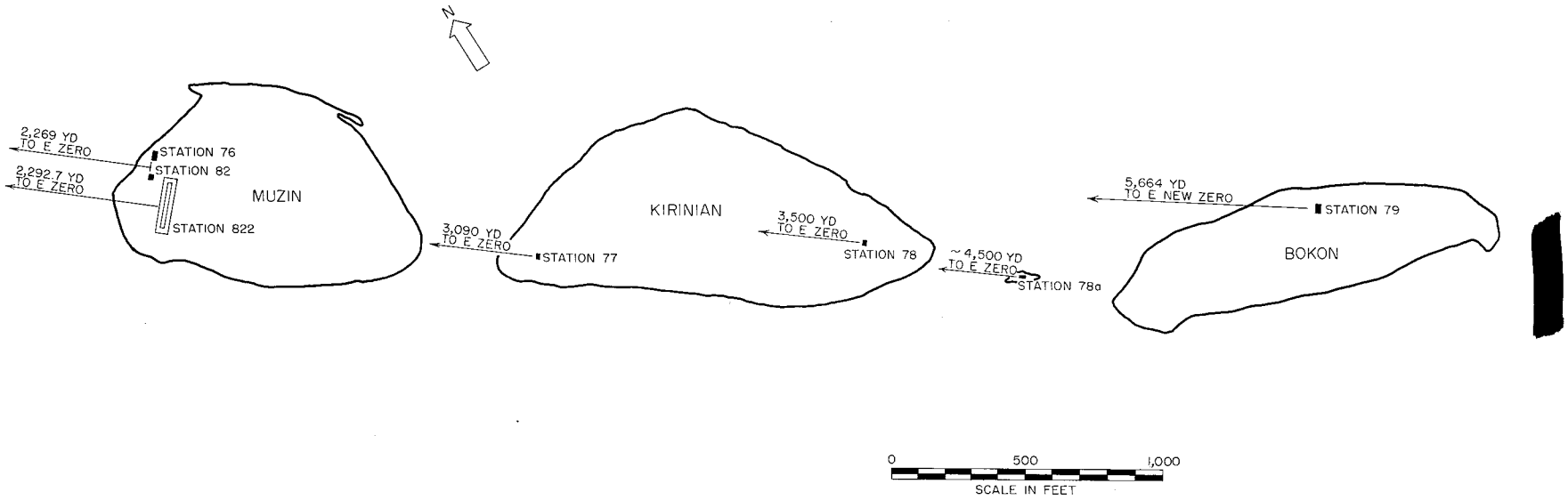


FIG. 4.10 Map of Muzin–Kirinian–Bokon, Easy Shot

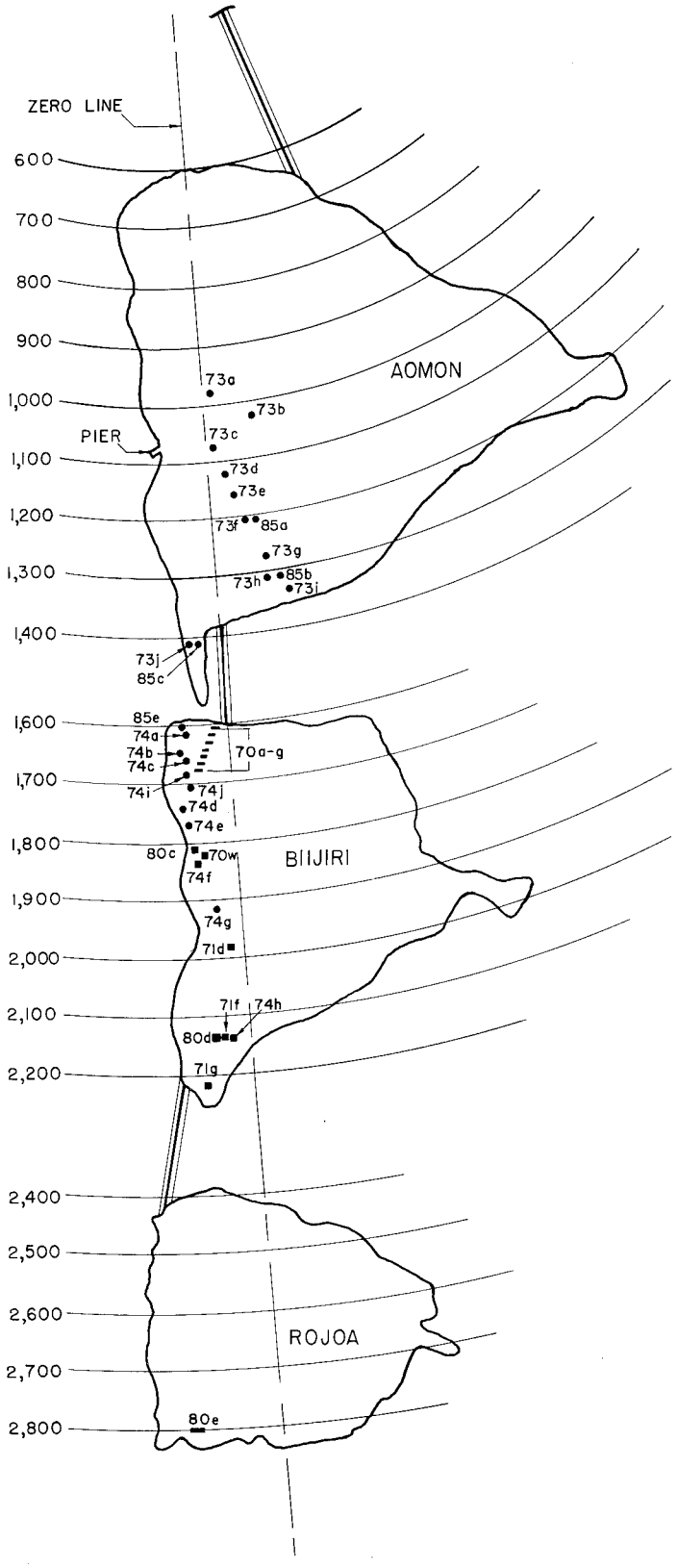


FIG. 4.11 Map of Aomon–Biijiri–Rojoa, George Shot

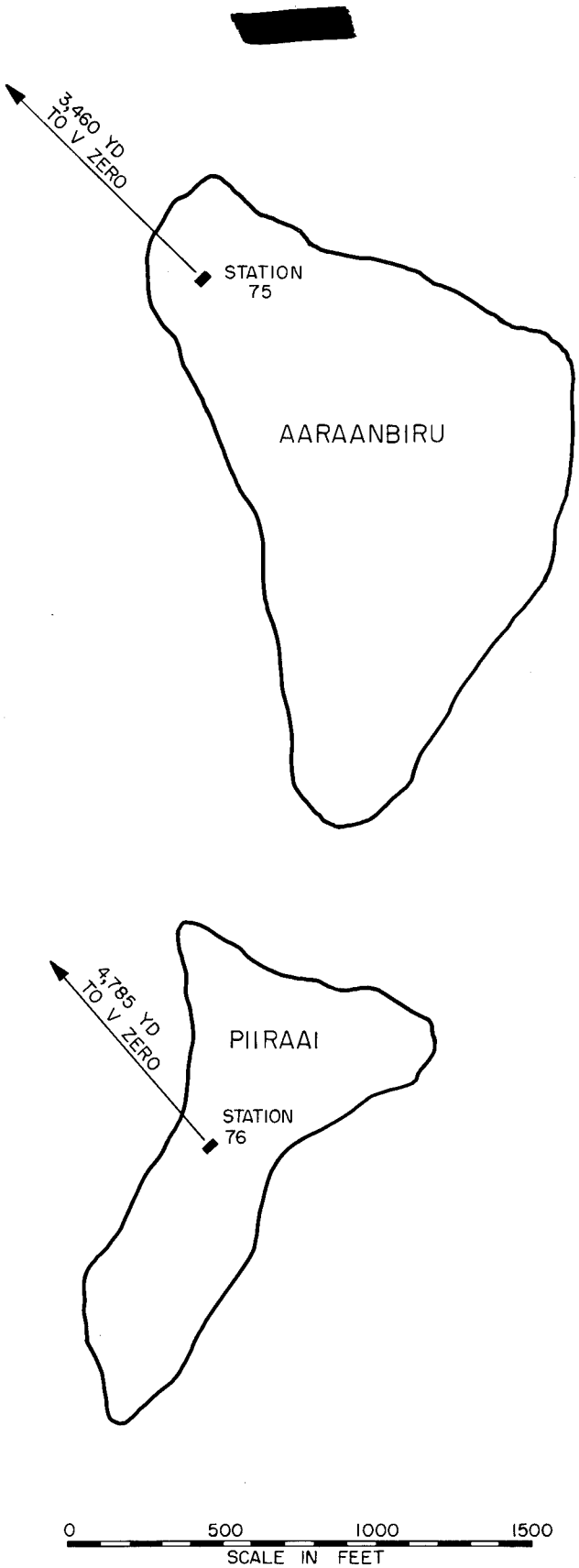


FIG. 4.12 Map of Aaraanbiru and Piiraai, George Shot

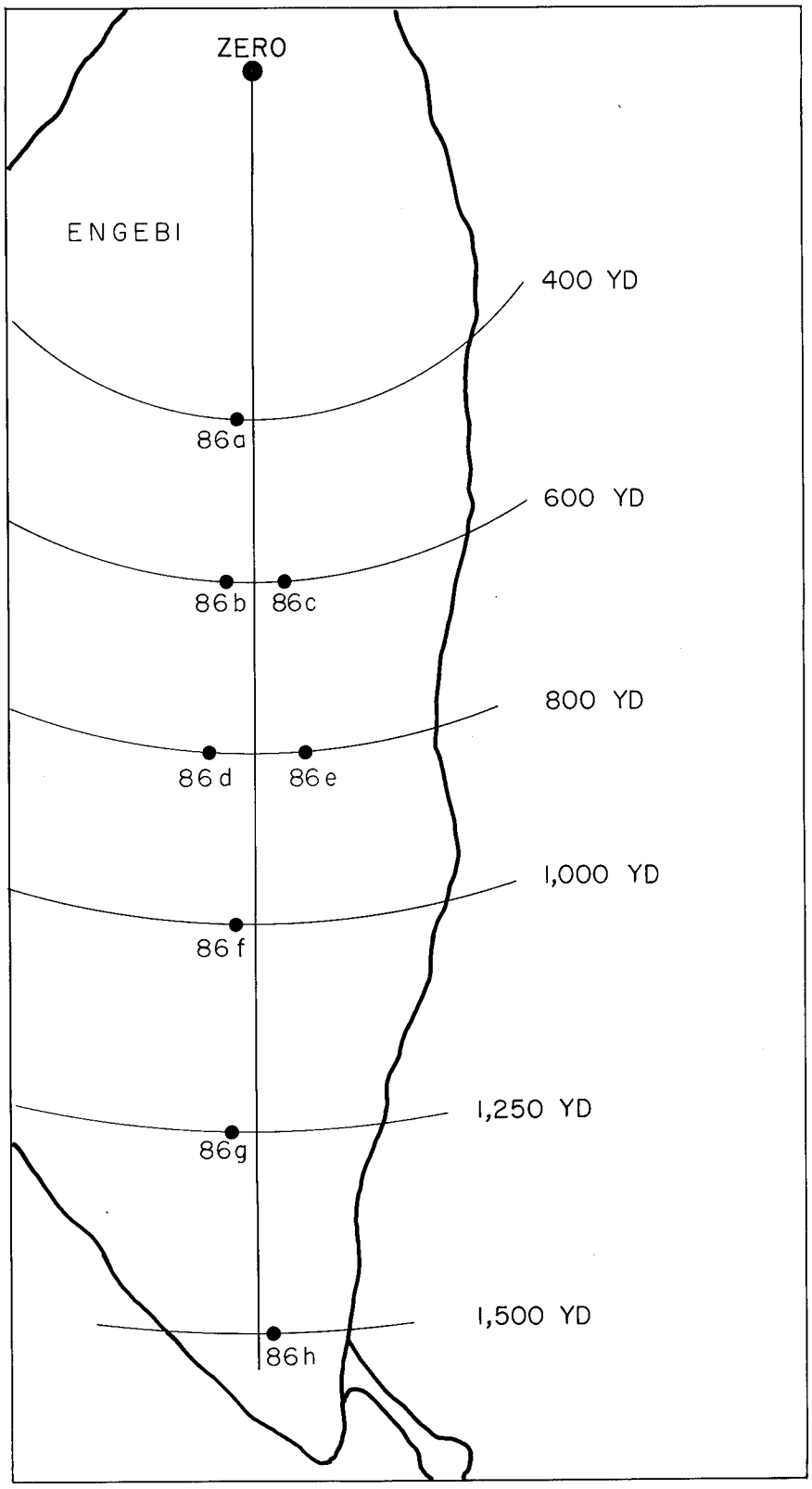


FIG. 4.13 Map of Engebi, Item Shot

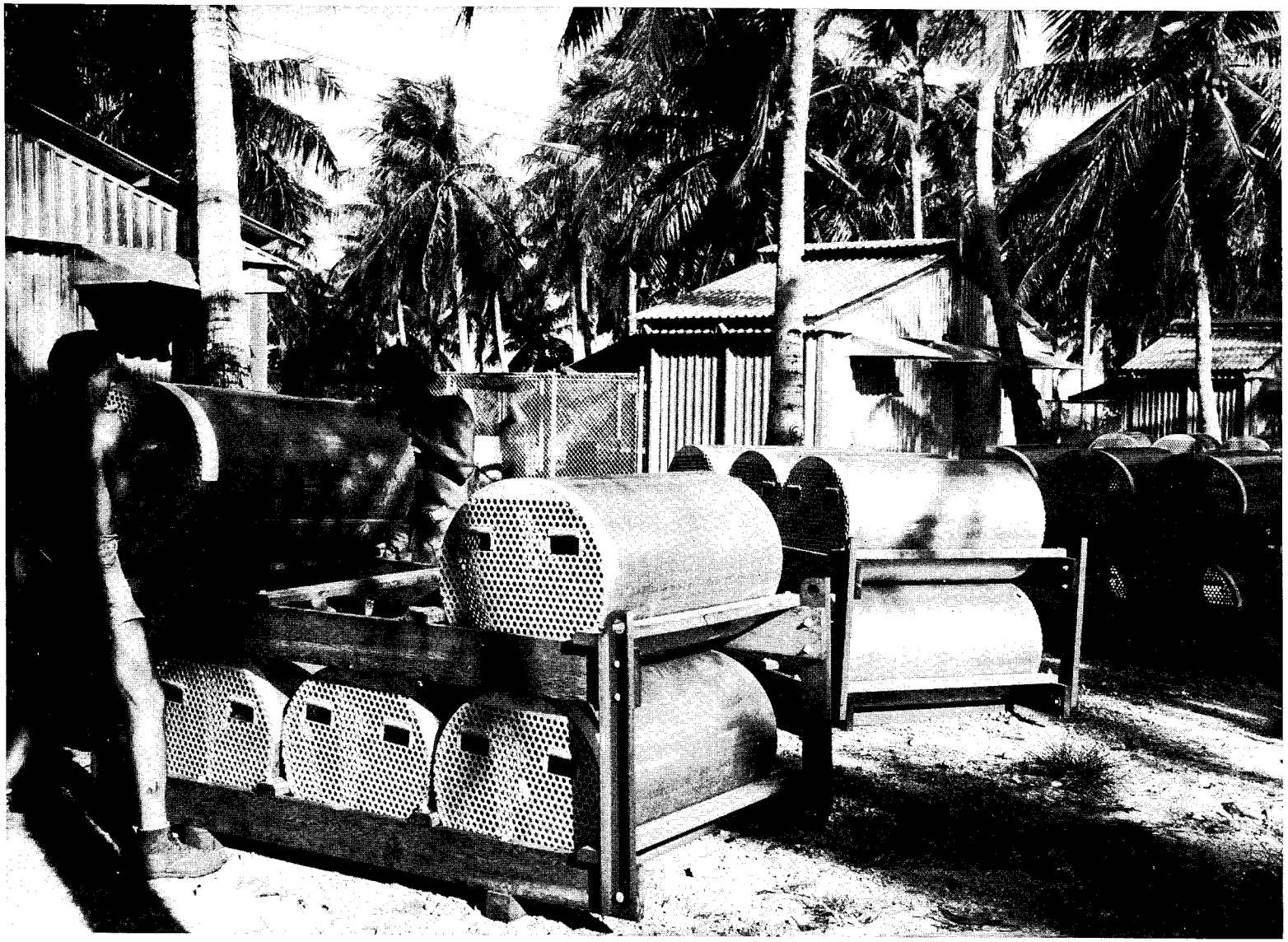


FIG. 4.14 Loading Liners on Barrel Pallets in the Animal Colony



FIG. 4.15 Use of Finger Lift to Facilitate Loading Barrel Pallets in the Animal Colony



FIG. 4.16 Loading Barrel Pallet on the Special Trunk with the Chain Hoist

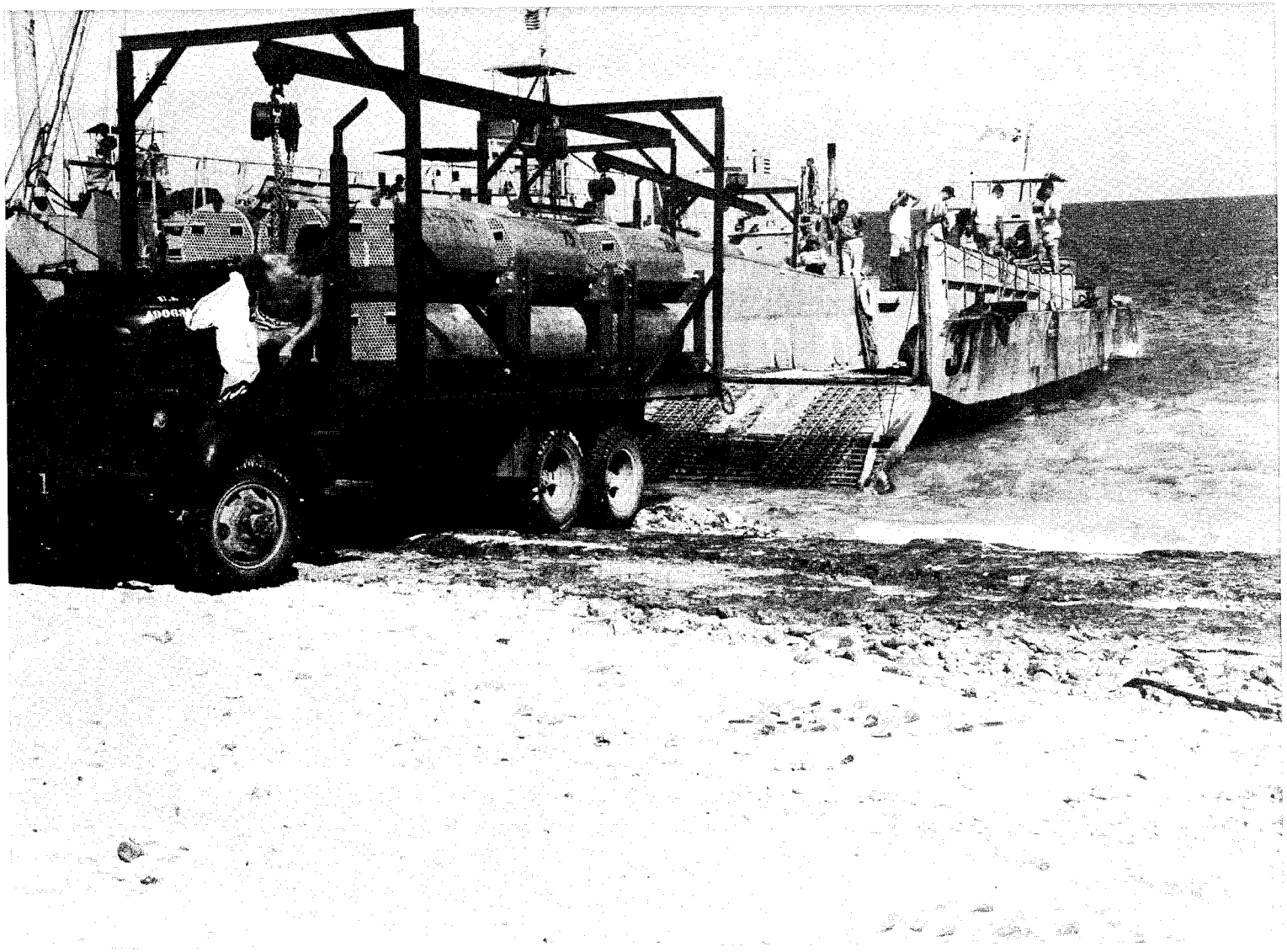


FIG. 4.17 Special Truck Loaded with Barrel Pallet Is Backed onto an LCM at Japtan

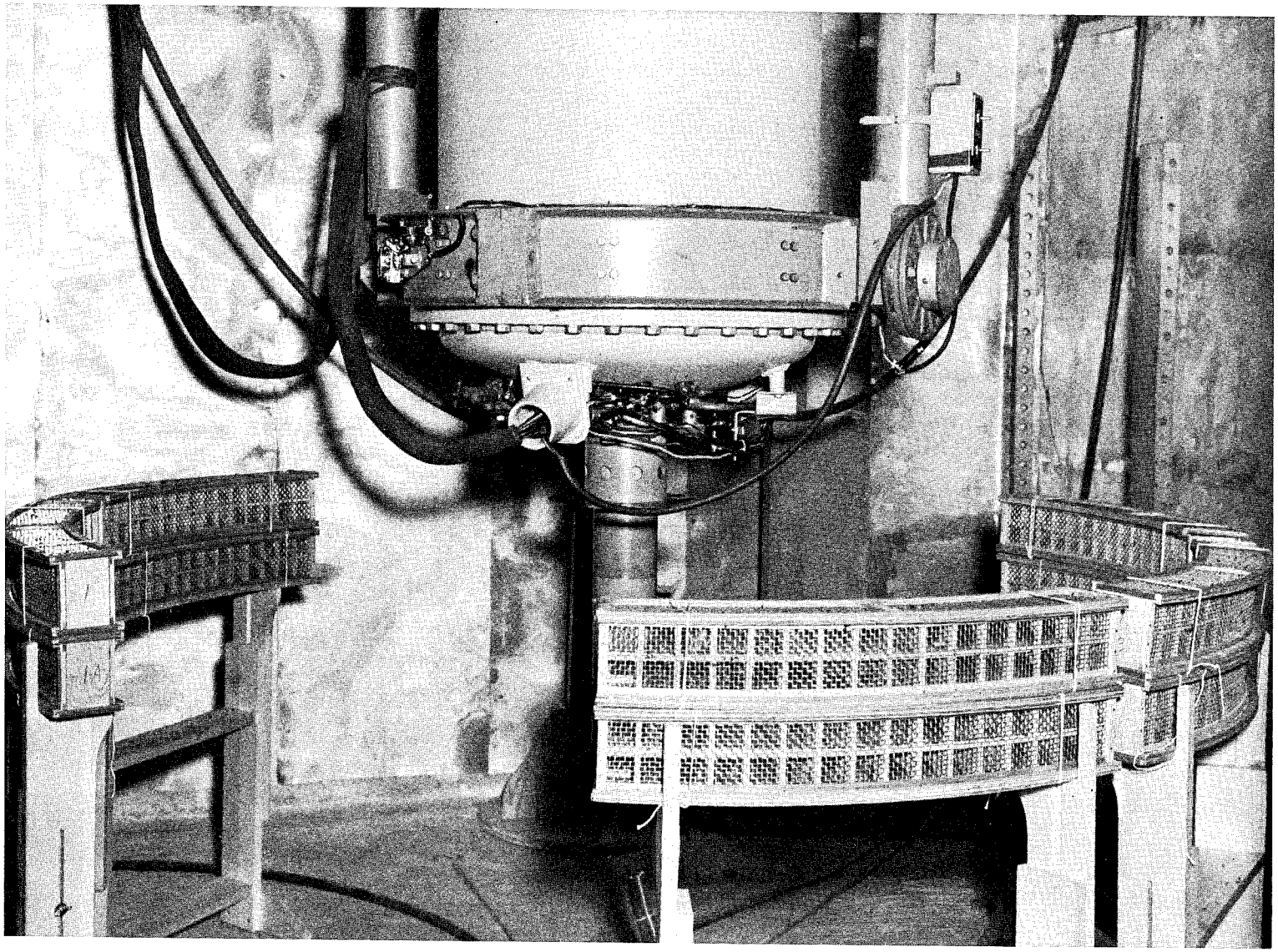


FIG. 4.18 Maxitron, 250-KVP X-ray Apparatus Installed on Japtan for Irradiation of Control Mice

Section 2

EVALUATION OF RESULTS

by

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and

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of

The University of Chicago

and

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Abstract

The results of the biomedical program are presented in a summary form and are evaluated critically. The gamma radiation of a nuclear weapon has a biological effectiveness for mice and dogs which is quite similar to that of X rays produced at 200 to 2,000 KVP. The determination of the LD_{50} of swine indicated that the gamma radiation from a nuclear weapon is almost twice as effective as 2,000-KVP X rays. This difference may be due to the greater volume of swine in relation to the higher effective energy of the radiation or to the use of younger animals in the field study. The values for the LD_{50} for swine and dogs were measured with a reliability within the limits of the 95 per cent confidence interval. The integrated biological effect of all bomb neutrons vs distance from the explosion was measured in terms of roentgens equivalent man of 230-KVP X rays using mice. The syndrome of whole-body radiation injury that was observed was similar to that observed in Japan, at Crossroads, and in laboratory studies. The flash burns inflicted by a nuclear weapon are identical to those produced with high-intensity sources acting for ⅓ to ½ sec. Using lucite spheres of varying wall thickness it was shown that the absorption of bomb gamma rays closely resembles the absorption of unfiltered 10-Mev betatron radiation. Occupants of aircraft passing through the stem of an atomic cloud are exposed to greater hazard from gamma radiation from external sources than from radiation from inhaled bomb debris. A foxhole 4 ft deep affords significant protection against gamma-radiation injury. In foxholes where radiation injury becomes lethal, primary blast injury is still not important. Probably the most significant single result of the field test was the demonstration that many of the most critical problems in the medical care of atomic casualties can be studied satisfactorily in the laboratory.

Chapter 1

Evaluation

1.1 INTRODUCTION

The experimentation of the biomedical program was successful in the sense that the majority of the objectives were attained. In this section the results are presented in summary form, and the interested reader is referred to the appropriate annexes for details of methods and results. An important feature of the planning for the 1951 program was the decision to study separately, so far as was possible, the biological effects of the field variables of a nuclear explosion. This decision precluded a study of mixed injuries of the sort that would be displayed by human casualties. In the present state of knowledge it seemed desirable to investigate certain fundamental aspects of the reactions of living organisms to nuclear and thermal radiation. In spite of the variety of the projects four common objectives can be followed throughout the program.

1. The use of biological dosimeters to measure the intensity of the field variables as a function of distance and to determine the relative biological effectiveness of the bomb radiations when compared to radiations from conventional laboratory sources.

2. Characterization of the quality of nuclear and thermal radiations in order that acceptable substitutes for a nuclear explosion can be developed in the laboratory for definitive studies.

3. Clinical and pathological studies to further clarify and characterize the syndrome of whole-body radiation caused by an atomic bomb.

4. The procurement of valuable educational material to facilitate the training of physicians and medical students for civil defense and military medicine.

1.2 DESIGN OF EXPERIMENTS

The performance of biomedical experiments in connection with field tests of nuclear weapons presents the investigators with unusual problems. Since the tests are conducted primarily to study new weapons, it may be difficult or impossible to make accurate intercomparisons or extrapolations of the results. Up to October 1951 biological material has been exposed at Hiroshima, Nagasaki, Crossroads, and Greenhouse. Each of the weapons has been different or has been fired under different circumstances. It is unlikely that a series of identical weapons will ever be fired solely for the purpose of repeating studies of the effects produced by the field variables. It will probably not be possible, therefore, to follow the common practice of performing a series of identical biological experiments to improve the reliability of the results or to define the variance of the material. This disadvantage can be offset to some extent by the use of large numbers of specimens for each test, but this in turn creates serious logistic problems. Since a weapons test is a "one-time" experiment from the standpoint of the biologist, it is necessary to select materials and plan studies which are appropriate. Studies of the dose-response type are particularly suitable for field tests since very accurate gradations of dose can be obtained and since all the subjects must be exposed simultaneously. When proper numbers of animals or plants can be used for each dose, it is possible to use biometrical techniques for the treatment of the data. It is generally recognized that in-

dividual species and strains of animals and plants may differ markedly in their inherent variability. The forms that have the least variance are obviously the most suitable for weapons tests, since smaller numbers can be used. The most desirable species from this standpoint, however, may have traits or peculiarities of growth which render their use in field studies difficult, if not impossible. For example, *Drosophila* is an excellent biological dosimeter, but it will not breed satisfactorily in the tropical environment of the Pacific Proving Ground. The special conditions of a weapons test are such that great care must be taken in planning so that the single test may have the greatest chance of success. Only those biological species whose behavior is very well known should be used for dose-response studies. If possible, paired control experiments should be conducted as nearly simultaneously as possible. In any case, all control studies should be realistic approximations of the test situation and should be an integral part of the program.

When experiments are planned that require biometrical treatment of the data, it is advantageous to consult with the statisticians in advance. This was done in preparation for the 1951 tests, and the numbers of animals exposed to a given dose and the number of stations for the reception of graded doses were determined with due regard for the type of analysis to which the data were subjected. Prior consultation on these problems often resulted in an economy of effort, but more important, it assured that the data which were collected could be analyzed. In general, all the statistical studies were planned so that results would be significant at the 95 per cent confidence level or better. All of the experimentation of the 1951 tests was of a simple type for which correlations could be expressed as a single regression equation. In the event that more complex, factorial-type studies are planned, collaboration with biostatisticians becomes even more important.

It is proper to attribute much of the success of the 1951 biomedical program to the long period of advance planning that was afforded. The preliminary studies were carried out over a period of at least 18 months in most cases, and over a period of 3½ years in the case of the burn study. When there is no prospect of repeating an experiment, it is imperative that every detail be planned carefully in advance. Makeshift equipment and temporary expedients should not be used. Electrical circuits must function properly, and the containers and apparatus used to expose the material to the blast must be sufficiently strong to assure that recovery is possible. Such assurance of the proper function of equipment can be had only by rigorous and careful testing before the field experiment is carried out.

1.3 LIAISON WITH PHYSICISTS

The design of a nuclear weapon has an important influence on the intensity as a function of distance of the field variables of interest to the biomedical investigator. It is not adequate to use scaled data for obsolescent weapons, such as the nominal atomic bomb, for the planning of field tests. The new principles, the examination of which is the reason for a weapons test may result in yields of the various forms of energy that cannot be predicted from simple scaling of the expected yield. As an example, the neutron flux at any given distance from a bomb detonation may be very dependent on the bomb assembly itself. In general, the theoretical physicists who planned the new weapon will have the most dependable conception of the results of its detonation. Close liaison with them will guarantee that the biomedical plans are realistic and at least capable of consummation. At every stage of the planning for the 1951 tests, the members of Group J–7 and Program 1, under the direction of Frederick Reines, provided invaluable assistance. In the course of the analysis of the data and the interpretation of the results, the same group have been equally helpful. The percentage of successful experiments would have been much smaller without this assistance. The obvious need for adequate technical information and guidance makes close liaison with the test director and his staff imperative.

It is worthwhile commenting, in this connection, on the obvious virtues of cooperative

research. There have been periods in the course of the atomic energy program in the United States when there was rigid compartmentation of technical information. This scientific isolation did not exist in Operation Greenhouse as far as Programs 1 and 2 were concerned. It was possible, for example, for the biologists responsible for studying the effects of neutrons, to consult freely with the physical scientists responsible for neutron measurements and with the theorists who were in a position to predict fluxes. The free interchange of ideas, plans, and information resulted in much better biomedical data than could have been obtained otherwise.

1.4 METHOD OF EVALUATION

The results of the biomedical program will be presented serially, treating each project or group of allied projects separately.

The schedule of the experiments for each shot is given in Tables 1.1 to 1.4 of Section 1. Since there were important differences between the four weapons tested, it will be necessary, as a rule, to consider separately the results obtained with each one. This method of presentation may be somewhat repetitious, but it will facilitate the preparation of a declassified report on Easy Shot if this is permitted at a later date.

The evaluation of each project is presented on three levels: (1) with respect to the adequacy of the experimentation, (2) with respect to the reliability and significance (in the general, not the statistical sense) of the data, and (3) with respect to the application of the data to the planning of future investigations and to the medical care of victims of nuclear explosions.

Chapter 2

Animal Colony (Project 2.1)

2.1 MICE

The mouse colony was established at Eniwetok well in advance of the 1951 tests for the reasons set forth in Section 1, Chap. 4. No serious difficulty was encountered in the production of an adequate breeding stock of L females and A males, and it was possible to provide the investigators with approximately 16,000 LAf_1 hybrid mice for test and control purposes. The operation of the mouse colony and the large-animal colony is described in another report,[1] and the results of the operation are summarized in Table 2.1.

TABLE 2.1 SUMMARY OF OPERATION OF ANIMAL COLONY

SHOT	NUMBER OF PROJECTS USING ANIMALS	NUMBER OF ANIMALS USED[a]		
		Mice	Swine	Dogs
Dog	3	1,170	...	...
Easy	11	11,390	178	164
George	4	1,230	22	...
Item	1		...	16
TOTALS		13,790	200	180

[a] Includes control animals used at Eniwetok.

The LAf_1 mice proved very satisfactory for LD_{50} determinations. They were less satisfactory than some other strains for spleen-thymus studies. The animals appeared to thrive in the tropical environment as evidenced by litter size, fraction of litter weaned, and rate of growth. The vital statistics of the mouse colony were substantially the same as for the same strain at the National Cancer Institute, Naval Medical Research Institute, and Naval Radiological Defense Laboratory. Mice of a given age displayed very small variations in body, thymus, and spleen weight. The variance in the radiobiological responses of the LAf_1 strain was also relatively small, a fact which contributed materially to the reliability of the data.

The animals tolerated well the unusual conditions imposed on them in the course of the experiments. These included cold and altitude in the drone aircraft, confinement in small cells in the cylindrical exposure units, transportation over rough water in landing craft, and the long trip by air from Eniwetok to Oak Ridge in the case of some of the survivors.

The experience with the mouse colony thoroughly vindicated the judgment of the representatives of the National Military Establishment who proposed it in 1949. It would have been very difficult to provide the same number of healthy animals in any other way. If the use of mice is contemplated in future tests, the LAf_1 strain can be recommended.

2.2 SWINE

The rationale for the early establishment of a large-animal colony was the same as in the case of the mice. It was believed that animals born and raised in the tropics would be better acclimatized to the total environment than would be the case if they had been reared there for only a few months. No evidence was obtained to support or controvert this belief. No special difficulties were encountered in the breeding program, with the exception of the timing. The litters were of average size and the fraction of the litters weaned was normal for the breeds used. In planning the breeding program there was insufficient al-

[1] Greenhouse Report, Annex 2.1.

lowance made for the rather large infant mortality in swine, which was the same at Eniwetok as occurred in the United States (34 per cent). As a result of this there were not enough Chester White shoats for the burn study, and it was necessary to use some of the smaller Landrace pigs. The initiation of breeding was inadvertently delayed for 1 month after the arrival of the breeding stock on Japtan. As a result of this the average weight of the pigs available at test time was 70 lb, while the original plans called for an average weight of 120 lb. There is no evidence that the smaller animals responded to the radiation in an unusual manner. Nevertheless, the reduction in size may have compromised the objective of the dose-mortality study (Project 2.4.1.4), which was to determine the median lethal dose (MLD) of gamma radiation for an animal of the same order of size (or volume) as an adult human.

It is well known that swine do not tolerate heat as well as other domestic animals. During the 36-hr period at Easy Shot the average weight loss due to confinement in the cylinder liners was 15 per cent. There were no instances of heat prostration in the course of the experiment, and it is not known whether the weight loss affected radiosensitivity.

Some of the Chester White shoats used in the burn study developed an eczematoid dermatitis, particularly after rainy periods. As a result of this their skin was not entirely satisfactory, although the effect of the disorder could not be evaluated with accuracy.

The breeding and rearing of the shoats probably did not involve much more effort per month than would have been required simply to feed and care for the same number of young pigs. It appears that there would have been less uncertainty if young pigs born in the United States had been shipped out 4 or 5 months in advance of the test. A saving of approximately 100 man-months (20 men for 5 months) might have been effected in this way. The availability of young animals of the proper age would necessarily depend upon the time of year of the tests. As an experimental animal, the pig has shortcomings: it is difficult to tame or train; it is difficult to obtain satisfactory samples of blood without undesirable trauma; and it appears to be delicate in comparison with the dog and the burro.

2.3 DOGS

The dog breeding program presented many difficulties. The breed selected, the Walker foxhound, was much less fertile than was anticipated, and when it appeared, in November 1950, that half the females were sterile, it was necessary to introduce 26 females and 6 males into the colony. Some of these animals developed distemper and a small epidemic occurred among the puppies that had been born at Eniwetok. As a result of these misfortunes the group of dogs available at shot time consisted of a mixture of young and old animals, all of which, however, were in excellent health. It was known that most of the adults were carriers of *Dirofilaria immitis,* since canine filariasis is endemic in the southeastern states, where the dogs were purchased. At Japtan there were no insect vectors for the disease, and none of the animals born there were parasitized. Intestinal parasites were well controlled in all animals. When the histological preparations were examined it was found that some of the animals were carriers of Fox encephalitis virus. There is no evidence that these conditions influenced the outcome of the dose-mortality study. Inspection of the mortality data suggested that smaller dogs were more sensitive to radiation. Analysis, however, showed no significant difference.

On the credit side, the dogs were gentle and easily tamed and trained. The response to radiation injury was quite consistent, and there is no good evidence to suggest that the mixed population which was exposed to the bomb was not a representative one radiobiologically. The dogs appeared to become acclimatized very rapidly and tolerated the heat and confinement in the exposure equipment quite well. It is believed that considerable effort and worry could have been saved by purchasing litters of puppies in the United States, and sending them to Eniwetok 4 to 6 months before the test. The animal holding facility

developed at the Naval Radiological Defense Laboratory would have been adequate for this purpose if sufficient litters were available.

2.4 SUMMARY

1. The animal colony was a satisfactory solution to the problem of providing adequate numbers of healthy animals at the time of the test.

2. When such large numbers of mice are concerned, it is best to ensure the supply by means of a special breeding program.

3. The LAf_1 mouse was well suited for radiobiological research, even under the adverse conditions that were obtained at Eniwetok.

4. Swine and dogs might have been supplied in adequate numbers in a more efficient manner than was used in Operation Greenhouse. Young animals could have been shipped out 4 to 6 months in advance of the tests, and acclimatized and reared to size in that period.

5. Dogs tolerated the climatic and other stresses of the field experiment better than pigs.

Chapter 3

Biological Dosimetry

3.1 INTRODUCTION

From the standpoint of clinicians and radiobiologists the biological effect of the nuclear radiation is the salient point of any effort to measure dose as a function of distance. Since it was not known that biological effects could be predicted from estimates of dosage obtained with physical instruments, it was appropriate to use biological dosimetry in the 1951 field tests. The biological system is essentially a secondary dosimeter, which must be calibrated using reliable instruments and a standard source of radiation. The extensive control studies of the systems used are presented in the appropriate annexes.[1] The broad objective of this portion of the biomedical program was to measure the biological effects of the ionizing radiations from atomic weapons. It has been speculated that the nuclear radiation might have unique properties because of the high intensity, the high average energy, the broad spectrum, and the uncertain proportion of neutrons and gamma rays. It was assumed that the biological effect would be an expression of the integrated action of this complex radiation. Five systems of biological dosimetry were employed: (1) weight change of the thymus of the LAf_1 mouse, (2) MLD of the LAf_1 mouse, (3) chromosomal aberrations in *Tradescantia,* (4) mutation and survival rate of *Glomerella,* and (5) abnormalities of growth of seedlings of corn. The results of these studies will be presented separately in the pages that follow.

[1] Greenhouse Report, Annex 2.2, Parts I, II, IV, and Part VI, Section 1.

3.2 CHANGE OF WEIGHT OF THE THYMUS AND SPLEEN OF THE MOUSE (PROJECTS 2.5.5.4 and 2.5.5.5)

This system of biological dosimetry was developed for use in laboratory studies of the biological effects of various types of ionizing radiation. The control studies[2] demonstrated that the LAf_1 mouse was a satisfactory subject and that the thymus was a more sensitive and more satisfactory indicator than the spleen for this particular strain. For this reason greater significance was attached to the thymic effects and the results with the spleen were used as check points. The regression line for decrease in thymic weight as a function of dose was improved by probit transformation so that reliable dose estimates could be made throughout the range 75 to 900 r. The error in estimate of an "unknown" dose on the basis of the per cent decrease in weight of the thymus 5 days after exposure was less than 15 per cent. For the purpose of the 1951 field test, the calibration curves were obtained with a 230-KVP X-ray machine at Eniwetok. These curves are given in Fig. 3.1. The equations for the curves after probit transformation are:

(thymus, females)

$$w = 0.1239 + 2.1557 \log r \pm 0.069 \text{ S.E.} \quad (3.1)$$

(thymus, males)

$$w = 0.6025 + 1.8749 \log r \pm 0.073 \text{ S.E.} \quad (3.2)$$

where r is the dose of 230-KVP X rays, w is the probit transformation of the per cent loss of weight of the thymus, and S.E. is the standard error of estimate.

[2] Greenhouse Report, Annex 2.2, Part I.

For purposes of comparison, the dose of X rays was considered to be expressed in roentgens equivalent man. The biological dose estimates to which significance is attached were all based on the effects observed on the thymus.

The hemispherical units in which mice were placed for this system of dosimetry functioned perfectly. For a detailed description of these units see the container report.[3] There were no mechanical failures and all animals placed in the units were recovered alive.

3.2.1 Results on Dog Shot

Gamma rays. Units of 30 mice were placed in each of the eight aluminum-domed stations of the 74 series at distances ranging from 1,550 to 2,100 yd from zero. (See Section 1, Table 3.1, and Fig. 4.8.) The distances were chosen on the basis of a late prediction of the yield of this weapon, 90 kt. The results are shown in Fig. 3.2, where equivalent dose in roentgens equivalent man is plotted against distance. National Bureau of Standards (NBS) film packs were placed inside the hemispherical units in the same geometry as the mice, and the dose estimates (uncorrected) from them are also plotted in Fig. 3.2. There is obviously good agreement between the two methods of dosimetry.[4]

Neutrons. Units of 30 mice were placed in each of the lead-domed stations of the 73 series at distances ranging from 900 to 1,300 yd. The estimate of dose for the animals at 900 yd is not reliable, since all but three of the animals in each station were dead before the 5th day. It can be stated that the dose received there was in excess of 900 rem. The results of the neutron exposure are given in Fig. 3.3, along with the curves for fast- and slow-neutron fluxes outside the lead hemispheres, obtained by Program 1 using sulfur and gold threshold detectors.

The location of the neutron stations was based on an early predicted yield of 140 kt. Due to a fortunate oversight the station locations were not changed when the later yield prediction of 90 kt was made. It is apparent that had the yield been 140 kt, most of the animals would have died before the 5th day. As it was, the good results on Dog Shot and the poor results on Easy Shot (see below) permitted favorable changes to be made in the plans for George Shot.[5]

3.2.2 Results on Easy Shot

Gamma rays. Units of 30 mice were placed in each of eight aluminum-domed hemispherical stations of the 74 series and in eight of the cylindrical stations of the 70, 71 series. The distances from zero ranged from 1,228 to 1,750 yd. (See Section 1, Table 3.2 and Fig. 4.9.) There was a difference in the geometry of the cylinder and hemisphere stations which is apparent from their shapes. In addition, there was a difference in the attenuation of the gamma radiation. The cylinder stations contained a large volume of unit-density material: mice, wooden racks, and mouse phantoms, and it was anticipated that scattering might modify the biological effects in these units. The dose measurements in the two types of units are given in Fig. 3.4. The film-pack estimates are included for comparison. The biological dosimeter indicated slightly higher doses, and the film indicated somewhat lower doses within the cylindrical units. It is probably correct to attribute this variation to attenuation by the various materials in the cylinder rack assembly. Good correlation is apparent between the NBS film-pack (uncorrected) values and the values estimated from the mice.

Neutrons. Units of 30 mice were placed in each of the eight lead-domed hemispheres of the 73 series. The distances from zero ranged from 675 to 1,000 yd. All the mice in the most distant station survived. Twenty-six of the 30 mice in the next station died before the 5th day, as did all the mice in the other stations. The high mortality rate among these animals was undoubtedly the result of

[3] Greenhouse Report, Annex 2.3, Chap. 3.

[4] Greenhouse Report, Annex 2.4, Part I, Section 1, is the detailed project report of the gamma-ray dosimetry.

[5] Greenhouse Report, Annex 2.4, Part I, Section 2, is the detailed report of the neutron dosimetry.

radiation injury. The random manner in which mice were selected from the colony precluded the possibility that the deaths were accidental. Autopsies performed at random on dead animals displayed the typical lesions caused by radiation. The high mortality rate in this experiment was also observed in the mice of the 85 series (see below), which were exposed to obtain survivors for life-time observation. In the latter group there were no survivors at 875 yd from zero (Station 85c) or closer. Practically all mice at 975 yd (Station 85d) and farther survived.

The biological dose anticipated at the stations of the 73 and 85 series was based on the best predictions available prior to the shot. At the time of firing of Easy Shot, the significance of the good results of Dog Shot was not appreciated. As a consequence, the lead-domed hemispheres were located at distances where the neutron flux should have been approximately 50 per cent greater than desired. In addition to this mistake, the absolute neutron flux per kiloton was greater from Easy Shot than from Dog Shot because of the nature of the assembly. In view of the compounding of errors, it is not surprising that few of the mice survived. This unsuccessful experiment is an example of one of the many problems that occur in field tests.

3.2.3 Results on George Shot

Gamma rays. Units of 20 mice were placed in each of eight aluminum-domed hemispheres of the 74 series at distances ranging from 1,620 to 2,160 yd. (See Section 1, Table 3.3 and Fig. 4.11.) The locations of these stations were based on a predicted yield of 250 kt. In all but the two most distant stations, the mice died of severe radiation injury before the 5th day. At 1,910 to 2,160 yd, the dose of gamma radiation was estimated to be 694 and 253 rem, respectively. The number of mice in each unit was reduced to 20 because statistical analysis of the earlier data disclosed that a satisfactory level of confidence could be obtained with the smaller number of animals.

Neutrons. Units of 30 mice were placed in each of eleven lead-domed stations of the 73 series at distances ranging from 1,000 to 1,500 yd. In the four closest stations all the mice died of acute radiation injury before the 5th day, and in the fifth station there were only nine survivors. In the distant stations all survived and could be used for dosimetry. The results are plotted in Fig. 3.5, along with the data for gold and sulfur neutrons outside and sulfur neutrons inside the lead shield. Units of 30 mice each were also placed in six lead-domed hemispheres of the 85 series. These animals were exposed to obtain survivors for studies of cataracts, etc. All of the mice exposed at 1,250 yd died within 30 days, while the majority placed at 1,350 yd or farther survived.

3.2.4 Studies in Drone Aircraft

The mouse thymus dosimeter system was also employed in drone aircraft at each of the first three shots. The results of this study are presented in Chap. 8.

3.2.5 Application of the Data, Gamma Rays

The data obtained from the mouse thymus dosimeters were used for other purposes than simple determination of dose in equivalent roentgens as a function of distance.

(a) In the control studies it was shown that the relation between weight loss of the thymus and dose was given by

$$r = ab^w \qquad (3.3)$$

where r is the dose, w is the per cent weight loss, a the y intercept, and b the slope of the regression line. Probit transformation gave a regression line that was linear with the log of dose. When dealing with quantal responses of this sort it is customary to measure the relative potency of two toxic agents by determining the ratio of the LD_{50}'s or of some other comparable valid point on the dosage-response curve. For the thymic weight response it is convenient to use the dose which resulted in a 75 per cent decrease in weight. The best data for comparison are those for female mice exposed in hemispheres on Dog and Easy Shots. The best estimates of dose of bomb radiation were those obtained using the Sievert ionization chambers. With these data,

the RBE was 0.84 and 0.81, respectively, which is to say that the gamma radiation is approximately 20 per cent less effective than 230-KVP X rays for producing weight loss in the thymus. It is proper to estimate RBE in this way since the slopes of the regression lines were comparable. The data are given in Table 3.1.

TABLE 3.1 DERIVATIVES OF BIOLOGICAL ESTIMATES OF DOSE

EXPERIMENT	RECIPROCAL OF REGRESSION COEFFICIENT (1/log b)	DOSE FOR 75 PER CENT WEIGHT LOSS[a] (r)	RELATIVE BIOLOGICAL EFFICIENCY[b]	MEAN FREE PATH, λ (meters)
Control, females	2.156	390		...
Dog, females (hemispheres)	1.895	460	0.84	407
Easy, females (hemispheres)	1.944	480	0.81	390
Easy, dose-mortality study (cylinders)		...	0.71–0.88	365

[a] For the control experiments dose was measured in air with a Victoreen ionization chamber. For the field experiment dose was measured in 0.5 to 3.0 cm of lucite with a Sievert ionization chamber.

[b] RBE is calculated as effective dose (230-KVP X rays) divided by effective dose (bomb).

(b) As a test of the reliability of the mouse thymus system of dosimetry, the data were used to calculate the mean free path of the gamma-ray photons. For this purpose the relationship between dose and distance was taken to be:

$$\log (rD^2)=\alpha+\beta D \qquad (3.4)$$

where r is either the dose in equivalent roentgens or the per cent loss of weight, D is the distance in yards, and α and β are arbitrary constants. Substituting for log r from Eq. 3.3 gives:

$$w \log b + \log a + 2 \log D=\alpha+\beta D \qquad (3.5)$$

and by differentiating Eq. 3.5 with respect to D, β is given by

$$\beta=\log b\left(\frac{dw}{dD}\right)+\frac{2 \log_{10} e}{D}. \qquad (3.6)$$

The mean free path, λ of the gamma photons is given by

$$\lambda=\frac{-\log e}{\beta}. \qquad (3.7)$$

Values for the mean free path of the gamma-ray photons from Dog and Easy Shots are given in Table 3.1, which also includes the estimates derived from the dose-mortality study. The results in the cylindrical stations of Easy Shot are in good agreement with the value reported by Program 1 (360 yd) and the value obtained in the phantom study (366 yd). When all the biological estimates are normalized to 92 kt, the result is 357 yd, an excellent agreement.

(c) Since biological effectiveness and the value for λ determined biologically were substantially the same for the gamma radiation from Dog, Easy, and George Shots, it was appropriate to combine the data and normalize them to the yield of Easy Shot, 48 kt. When this is done the dose in roentgens equivalent man times the distance squared (rD^2) can be plotted against distance to give the curve shown in Fig. 3.6. The equation for the best line of fit for this curve is:

$$\log [(rD)^2\times 10^{-7}]=3.7372-0.001187\ D. \qquad (3.8)$$

The values in r for gamma-ray dose reported for the NBS film packs were also normalized to 48 kt and plotted in the same manner on Fig. 3.6. The equation for the curve from the film data is:

$$\log [(rD)^2\times 10^{-7}]=3.7111-0.001130\ D. \qquad (3.9)$$

The ratio between these curves is 0.94. This treatment of the data demonstrates the close similarity of the response of the mouse thymus dosimeter calibrated with 230-KVP X rays, and the NBS film dosimeter calibrated with 600-KVP X rays.

(d) If it is assumed that the observed biological effect is directly proportional to the gamma-ray dose, and if there is no significant difference between the gamma-ray spectrum emitted by the three weapons, it is possible to determine the ratio of the kilotonnages. The yield of Dog Shot was taken as 92 kt, and the yields of Easy and George Shots were

scaled on the basis of the biological effects. The results are shown in Table 3.2. The accepted values for yield determined by Program 1 are shown for comparison. In general, the agreement is good. There is sufficient data available to explain the discrepancies between these estimates.

TABLE 3.2 BIOLOGICAL DATA USED TO SCALE WEAPON YIELDS ASSUMING DOG SHOT AS 92 KT[a]

EXPERIMENT	MOUSE THYMUS DOSIMETER	NBS FILM PACK	BEST ESTIMATE OF PROGRAM 1
Easy, hemisphere	37	41	46.7
Easy, cylinder	47	35	46.7
George, hemisphere	320	350	215

[a] Program 2 has consistently used the revised estimate of 92 kt for Dog Shot; the final estimate by Program 1 based on radiochemistry is 82.9 kt.

3.2.6 Application of the Data, Neutrons

The response of the mice exposed to neutrons was consistent and was clearly related to the probable dose. No difficulty was encountered in making an estimate of the dose of radiation in roentgens equivalent man inside the lead hemisphere, which for the purpose of this experiment was taken as equal to the number of roentgens of 230-KVP X rays required to produce the same effect. Before the experimental results could be used to predict the neutron dose in the absence of shielding, it was necessary to make a theoretical examination of the effect of the lead shield on the incident neutrons. The results of this study are given in the annex containing the project report.[6] Also included in the project report is a consideration of the significance of certain physical measurements made by Project 3.1.1.5 and the examination of gold and sulfur threshold detectors displayed inside and outside the lead-domed hemispheres.

When the data on neutrons is considered, it should be borne in mind that the bombs detonated on Dog and Easy Shots were typical of fission weapons. The George Shot bomb was an experimental assembly resembling no present or contemplated weapon and the results of this shot should therefore be considered atypical. The pertinent conclusions from the assessment of the physical data may be summarized as follows:

1. The 7-in. lead hemisphere provided excellent shielding from the bomb gamma rays. The most pessimistic considerations indicated that the gamma dose inside the closest hemisphere from which usable data were obtained was less than 30 r.

2. Outside the lead hemispheres the gold neutron flux (0 to 0.4 ev) was approximately 10 times greater than the sulfur neutron flux.

3. The apparent transmission of gold neutrons by the lead hemisphere ranged from 60 to 80 per cent. The transmission was slightly higher than indicated by theoretical considerations. The apparent discrepancy may be explained on the basis of the degradation of neutrons having energies of 0.4 to 0.7 ev outside the lead.

4. There was an apparent transmission of sulfur neutrons (>3 Mev) of 20 per cent on all shots. The other 80 per cent did not represent a net loss of radiation effect. The neutrons were merely degraded in energy to the 1- to 3-Mev range regardless of their initial energy and were not detected by the sulfur threshold detector which has a sharp threshold at 3 Mev.

5. The lead shield produced only a negligible change in the total neutron flux and a negligible decrease in the total energy of the intermediate energy neutrons. The most significant effect of the shield was degradation of neutrons of energies of 3 Mev or greater down into the 1- to 3-Mev energy range.

The biological results presented in the project report showed that the spleen-thymus effectively integrated the biological effect of bomb neutrons in the range of biological interest. These results gave a direct measurement in roentgens equivalent man of the radiation dose of neutrons through a 7-in. lead shield. Theoretical considerations of the effect of the lead shield on gold (0 to 0.4 ev), sulfur (>3 Mev), and intermediate neutrons permitted estimation of the radiation dose due to neutrons in the absence of any shielding.

[6] Greenhouse Report, Annex 2.4, Part I, Section 2.

The biological results are summarized as follows:

1. The fraction of the biological neutron dose due to gold neutrons was negligible.

2. The biological effects of neutrons of intermediate energies constituted from 50 to 75 per cent of the total neutron dose on Dog and Easy Shots. They constituted much less of the total neutron effect on George Shot.

3. The biological effects of sulfur neutrons constituted 25 to 47 per cent of the total neutron dose on Dog and Easy Shots and 75 to 95 per cent of the neutron effect over the range of biological interest on George Shot.

4. Over 90 per cent of the bomb neutron dose from any of the bombs was due to neutrons with energies greater than 1 Mev.

5. The neutron dose from the bombs did not scale directly as kilotonnage but depended on the bomb assembly. From the results it is reasonable to predict that the neutron dose per kiloton will be a minimum for a Dog-type bomb assembly, intermediate for an Easy-type assembly, and a maximum for the assembly type used at Hiroshima.

6. The ratio of neutron dose to gamma dose for the three bombs was not constant per kiloton. Table 3.3 shows the ratios of neutron to gamma-ray dose for Dog, Easy, and George Shots at points of equal distances and equal neutron dose (in roentgens equivalent man). These results show that the neutron to gamma-ray dose varied approximately 1 to 11 per cent with the various assemblies over the range of biological interest.

TABLE 3.3 THE NEUTRON TO GAMMA-RAY DOSE RATIOS FOR DOG, EASY, AND GEORGE SHOTS AT POINTS OF EQUAL DISTANCE AND EQUAL NEUTRON DOSE
(In roentgens equivalent man)

REFERENCE POINT	NEUTRON TO GAMMA-RAY DOSE (PER CENT)		
	Dog	Easy	George
560 rem	3.6	11.4	1.8
1,000 yd	4.0	11.4	...
1,250 yd	3.0		1.5
1,500 yd	...		1.4

7. The 7-in. lead shield decreased the total dose due to neutrons by only 4 to 16 per cent, depending principally on the proportion of intermediate to sulfur neutrons for the various assemblies at the various distances where the observations were made.

On the basis of the foregoing statements it follows that the mice inside the lead hemispheres were exposed to a spectrum of neutrons which differed from the incident flux. The principal difference was due to the moderation of neutrons having energies of 3 Mev or greater down into an energy range of less than 3 Mev. This difference, however, amounted to only 4 to 16 per cent and was somewhat dependent on bomb assembly characteristics. It is therefore reasonable to say that the neutron dose measured behind 7 in. of lead is a good approximation of the neutron dose in the absence of any lead shielding.

Current military and civil defense planning is concerned with the protection of personnel from the radiation effects of an atomic bomb. Such protection raises questions regarding the efficiency of shielding and the possibility of evasive action. In all such plans the assumption has been that neutrons from an atomic explosion represent a negligible radiation hazard as compared with that due to gamma rays. This assumption is based on theoretical considerations and on measurement of apparent neutron spectrum and flux using gold and sulfur threshold detectors. There is obviously a very large energy range from about 0.4 ev to 3 Mev for which no physical and biological experimental information was available prior to Operation Greenhouse. Prior to the present experiment it was anticipated, but not established, that the biological effects of bomb neutrons were due chiefly to neutrons of intermediate energies.

This investigation of the importance of neutron irradiation from an atomic explosion using biological dosimeters has the following important consequences especially with regard to military and civil defense planning.

(a) Evasive action by personnel may not be highly effective against neutrons as the majority of the dose is delivered by fast neutrons of greater than 1 Mev energy.

(b) Any future studies to determine the effect of neutron shielding must be evaluated by using biological systems until efficient neutron detectors are developed which respond to neutrons of intermediate energy.

(c) The ratio of neutron to gamma-ray dose from an atomic explosion is dependent on weapon assembly and does not scale with kilotonnage. Neutrons constitute a negligible part of the total radiation dose over the range of biological interest for weapons of the standard implosion type. The fraction of the dose due to neutrons may not, however, be insignificant for weapons of drastically different design.

3.2.7 Evaluation, General Comments

The practice of biological dosimetry based upon the per cent decrease in weight of the thymus of the mouse was a successful application of the techniques of quantitative biology. The animals were quite satisfactory, and appeared to respond to the effects of radiation in a very consistent manner. Considerable effort is required to use mice as dosimeters and rigorous attention to details is necessary. With animals as homogeneous in their response as LAf_1 mice, it was possible to use two-thirds the numbers that were employed in the control studies. Although weighing the spleen is simpler than weighing the thymus, the latter organ yields the more reliable data when using the LAf_1 strain of mice. The results were not improved materially by including studies of the water, nitrogen, and potassium content of the thymus and spleen.

The exposure units functioned perfectly without exception. On the basis of the experience gained in the 1951 tests, the units could be simplified without compromising their efficiency. The basic principles of the design of these units appear to be sound, and there is no good reason why larger units could not be constructed to accommodate larger animals, if desired.

The principal shortcoming of these experiments (Projects 2.5.5.4 and 2.5.5.5) was the number and location of the stations. It was known that the yields of the three weapons (Dog, Easy, and George) were uncertain, and it was expected that every station would not provide useful data. It appears now that the additional effort involved in the use of more stations would have been justified. However, since the results of three shots could be pooled in most instances, sufficient data were available for an exhaustive but rewarding analysis of the results.

There does not appear to be any sound basis for questioning the reliability of the data within the measured limitations of the method. The careful controls, both general and special, and the random manner in which mice were selected for and assigned to stations should have prevented the occurrence of any systematic bias. When the results obtained with this biological dosimeter are compared with other methods of measuring such field variables as mean free path of gamma photons and yield of the weapon, the correspondence is surprisingly good.

3.2.8 Evaluation, Gamma-ray Study

The measurement of gamma-ray dose as a function of distance, using mice, did not provide any new physical information regarding the gamma radiation itself. It was important to determine the biological effectiveness of the gamma radiation for the mouse thymus system. It was found that the radiation produced by the weapons was approximately 20 per cent less effective than 230-KVP X rays, as measured by the effect on the thymus. Because of the higher energy of the gamma rays this difference is not unexpected, and it is not sufficient to invalidate fundamental radiobiological studies of mice using ordinary X rays. This result, when considered in relation to other estimates of the RBE (see below) warrants the conclusion that atomic bomb gamma radiation is not uniquely effective or ineffective biologically. Finally, the demonstration that the biological dose and the dose measured with the NBS film pack are quite similar is important. Since this is the case, there is no good reason to use the mouse thymus dosimetry system for gamma rays in future tests. The results obtained with properly calibrated film packs can be accepted confidently as equivalent to the biological dose in mice.

3.2.9 Evaluation, Neutron Study

Although the relative biological effectiveness of various energies of neutrons was not measured in the 1951 field tests, it is apparent that differences in the theoretical RBE of a factor of 3 or 4 will not affect the principal conclusions of the study.

The mouse thymus system is an excellent relative dosimeter for neutrons. The mice are quite responsive to neutrons of energies for which no good threshold detector is available. It is difficult to see how it is possible at the present time to perform adequate studies of shielding without using a biological system. Moreover, it is apparent that shielding studies that depend upon sulfur or other threshold detectors may be very misleading, particularly to unsophisticated workers. In the lead hemispheres, the fast neutrons inside were fewer by a factor of 5 than outside, when the measurement was made using sulfur. It appeared, however, that the mice responded in an appropriate manner and according to predictions based on physical theory.

The main objection to the use of mice as neutron dosimeters is the effort involved, particularly the logistic effort. Other biological systems should be studied, and tests performed with those which can tolerate a more varied environment and which require less effort to handle.

3.3 DETERMINATION OF MEDIAN LETHAL DOSE FOR THE MOUSE (PROJECT 2.4.1.1)

3.3.1 Introduction

The dose-mortality response of the LAf_1 mouse was investigated for three reasons:

1. The MLD, or the $LD_{50/28}$ has a characteristic value for this species.[7] Under proper conditions, various points on the dose-mortality curve can be used to verify estimates of dose in roentgens equivalent man determined by other means.

[7] The MLD or the LD_{50} is defined as the dose (of radiation) estimated to kill, in a stated period of time, one-half the total population from which the sample was drawn.

2. Control studies demonstrated that the slope of the dose-mortality curve, and to a lesser extent the MLD bears some relation to the quality of the radiation.[8] Although no precise estimates of quality were anticipated, it is possible to match the slopes of experimental and control curves and to make a reasonable inference therefrom.

3. The hybrid mouse is used extensively for laboratory studies of protective and therapeutic agents. Ideally such experiments involve determination of the unmodified and modified dose-mortality response to X rays of some convenient energy such as 200 to 2,000 KVP. It was believed that a knowledge of the RBE of atomic bomb gamma rays would be useful to investigators of these agents.

Control studies of the dose-mortality response of the LAf_1 mouse showed that after probit transformation mortality is a linear function of arithmetic dose. In this circumstance dose and mortality are related by the equation

$$y=a+bx \tag{3.10}$$

where y is the per cent mortality expressed in probits, x is the dose, a is the y-axis intercept, and b is the slope of the regression line. Relative potency, or RBE, can then be determined as follows if the a intercepts are equal:

$$\text{RBE}=\frac{b_{\text{bomb}}}{b_{\text{X ray}}}=\frac{1/(\text{LD}_{50})_{\text{bomb}}}{1/(\text{LD}_{50})_{\text{X ray}}}=\frac{(\text{LD}_{50})_{\text{X ray}}}{(\text{LD}_{50})_{\text{bomb}}}. \tag{3.11}$$[9]

In the course of the Control Studies it was apparent that the radiation factors had a marked influence on the results. The most important factor appeared to be the extent and nature of the scattered radiation to which the animals were exposed. Scattering influenced both the LD_{50} and a, the y-axis intercept in the following manner:

SCATTER	LD_{50} (r measured in air)	a (y-axis intercept)
Minimal	760	−2
Considerable	550	−9

[8] Greenhouse Report, Annex 2.2, Part VI, Section 1.
[9] Greenhouse Report, Annex 2.2, Part VI, Section 1.

With the realization of the significance of these factors, it was appreciated that an absolute value for RBE was unlikely. It seemed probable, however, that the field data could be paired with appropriate control data to yield a good first approximation of the RBE.

3.3.2 Discussion of Results [10]

The original plans called for a dose-mortality study at Easy and George Shots. The experiment at Easy Shot only was performed, and the mice assigned to George Shot were used for additional control studies. The mice were placed in 28 single cylinder units, designated as the stations of 70, 71 series. Each station contained 220 mice for the dose-mortality study, with the exception of the nine closest stations, each of which held 60. (See Section 1, Table 3.2 and Fig. 4.9.) The dose-mortality response of the LAf_1 mice is shown in Fig. 3.7, where the per cent mortality is plotted against the dose of bomb gamma rays. The values for dose as a function of distance consisted of the readings of the ionization chambers placed inside spheres with walls consisting of 3 cm of lucite and the air absorption coefficient (reciprocal of the mean free path) determined biologically. The probit transformation of this typical sigmoid survival curve resulted in the regression line shown in Fig. 3.8. The $LD_{50/28}$ was 759 ± 2.2 r and this dose was delivered at 1,416 yd. The low variance of the data is clearly shown in Fig. 3.8 and is good evidence of the remarkable consistency of the response of this strain of mice to ionizing radiation. When the dose at 1,416 yd is read from the curve obtained with the mouse thymus dosimeters inside the cylinder stations (Fig. 3.4), the result is 675 r, which is considered to be a good agreement. When the dose at 1,416 yd is read from the curves obtained with NBS film packs, the $LD_{50/28}$ is found to be 610 r, which is only fair agreement and is attributed to the energy dependency of the film. If a correction factor [11] of 1.25 is applied to the film data, the dose at 1,416 yd becomes 763 r which is excellent agreement.

The probit regression line for arithmetic dose obtained at Easy Shot had a slope (b) of 1.60, and the y intercept (a) was approximately -7. In terms of the control studies, bomb radiation can be characterized either with respect to the slope or the intercept, or both. The slope at Easy Shot was comparable to those obtained in control studies at the Naval Radiological Defense Laboratory, using a filtered, conventional beam and an experimental situation where back-scatter varied from 9 to 19 per cent. When the field data are paired with control data from the Naval Radiological Defense Laboratory, where the slopes and intercepts were approximately equal, the RBE was found to vary from 0.85 to 0.72. The latter value was associated with the greatest scatter in the 230-KVP reference source. When the field data were paired with the control experiment at Japtan where comparable physiological stress was imposed, the RBE was 0.88. When the field data are compared with results obtained with the supervoltage (2,000-KVP) source, the RBE was unity. In the case of the Japtan and the Naval Medical Research Institute (supervoltage) experiments there was no similarity between the slopes and intercepts obtained with bomb radiation. The relevant data are presented in Table 3.4.

Regardless of the manner in which RBE is calculated it is apparent that the bomb's gamma radiation is 12 to 20 per cent less effective than 230-KVP X rays in the production of the dose-mortality response. In contrast to this the RBE with respect to 2,000-KVP X rays is unity. It is of interest to speculate on the significance of the other parameters of the dose-mortality curve obtained in the field. It appears that the gamma radiation from the bomb resembles the filtered, conventional, transmitted X-ray beam with respect to slope

[10] Greenhouse Report, Annex 2.5, Part I.

[11] M. Ehrlich and S. H. Fitch, "Photographic X- and Gamma-Ray Dosimeters," *Nucleonics*, IX (1951) 5–17. The film packs were calibrated with 800-kv X rays, and also with X rays from the 10-Mev betatron. The correction factor of +25 per cent was obtained with the latter.

[redacted]

TABLE 3.4 ESTIMATION OF RBE OF BOMB GAMMA RAYS USING DOSE-MORTALITY RESPONSE OF LAf_1 MICE

EXPERIMENT	LD_{50}	SLOPE OF PROBIT LINE (b)	y INTERCEPT OF LINE (a)	RBE[a]	ENERGY OF X RAYS (KVP)
Easy Shot	759	1.60	−7		
Japtan, stress[b]	675	1.28	−3	0.88	230
USNRDL–1[c]	648	1.76	−6	0.85	250
USNRDL–2[d]	547	2.38	−8	0.72	230
NMRI[e]	761	0.83	−2	1.00	2,000

[a] RBE calculated as $\frac{(LD_{50})_{\text{x ray}}}{(LD_{50})_{\text{bomb}}}$.

[b] The mice were exposed to environmental stress equivalent to that experienced at the field test. Radiation delivered with minimal back-scatter.

[c] Radiation delivered with 9 per cent back-scatter. LD_{50} is not corrected for scatter.

[d] Radiation delivered with 19 per cent back-scatter. LD_{50} is not corrected for scatter.

[e] Radiation delivered with minimal back-scatter.

and intercept. The physical conditions of exposure in the field were such that it is reasonable to believe that the radiation was well filtered by several thousand feet of air, and extensively scattered by the cylindrical exposure unit and its contents. In this respect the field irradiation conditions were similar to those at the Naval Radiological Defense Laboratory. It is not possible with the data available to do any more than record these speculations.

The investigators devoted much time and effort to an analysis of the time of survival after exposure. It was finally concluded that there was no obvious correlation between dose or mortality and the mean survival time in the range of doses employed, *i.e.*, from approximately LD_0 to LD_{100}. In the range of supralethal doses, the mean survival time is clearly a function dose, but there is no apparent influence of the quality of the radiation on this effect.

3.3.3 Evaluation

The investigators responsible for Project 2.4.1.1 encountered many difficulties, which are described in detail in the control and field reports. The principal difficulties which have a bearing on evaluation were the following:

1. There was a considerable variation in the control results which appeared to be related to the physical factors of the irradiation and the inherent difficulty of translating air dose into tissue dose. The different values for LD_{50} and for the slopes of the probit regression lines are given in Table 3.4. Justifiable corrections could be applied to the field and control values for LD_{50}, but it was not possible to adjust the slopes, or even to elucidate the factors responsible for the discrepancy.

2. The construction of the trays in which the mice were placed for exposure to the weapon radiation was not satisfactory. The individual cells were too small, 2 by 3 by 1¾ in. high, and were not adequately ventilated. As a result of this the mice lost an average of 15 per cent of their body weight during the 36- to 40-hr period of confinement. A special control study was conducted to determine the effect of this stress on radiosensitivity, and it was found that at the LD_{50}, the mice tolerated 60 r, or approximately 10 per cent more radiation than unstressed controls. The physiological disturbance due to confinement did not appear to compromise the experiment, but it was not an ideal situation.

3. The cylindrical exposure units were designated to accommodate a maximum of 270 mice. The animals were placed in cells in six plywood trays with perforated aluminum covers and with individual aluminum water cups in each cell. Cells that did not contain mice were filled with "mouse phantoms" made of masonite. In this way the geometry was kept constant. The assembly of six trays, fully loaded, weighed 40 lb and measured 42 by 10 by 12 in. high. In effect, it was a large unit-

[redacted]

density phantom with "dosimeters" distributed throughout it. The combination of scattering and attenuation of the gamma radiation within this phantom is not known with certainty. The film in the mouse phantoms was energy-dependent, and the readings require a correction, the extent of which cannot be determined. Since the mice were individually numbered and since their location within the tray assembly was known, it was possible to analyze the mortality data at a given station for the effect of position. A top-to-bottom and a front-to-back gradient (with respect to the bomb) was found. The full significance of this gradient cannot be assessed because all the trays were loaded in a similar manner, with the result that mice of a given category (as small, young females) always occupied the same position in each exposure unit. The mortality data has been submitted to a statistical analysis with respect to the influence on lethality of age, sex, weight, and position within the exposure unit. The preliminary summary results are given in Appendix A of this section. In retrospect, it is remarkable that the variance of the dose-mortality curve was as small as it was. In any case, it is not possible to present a measured value for dose inside a given exposure unit. The readings of the NBS film packs are not adequate since they were not inside the tray assembly. After the difficulties have been enumerated, it is proper to record the fact that the logistical problems which seemed very great were solved satisfactorily. Approximately 6,000 mice were exposed in the cylindrical units and none were lost, killed, or misplaced in the course of the operation.

The mouse dose-mortality study had two significant results:

1. It was in agreement with the results obtained with the mouse thymus dosimeter with respect to the determination of the RBE of the gamma radiation of a nuclear weapon. In both cases the RBE was shown to be approximately unity.

2. It was possible to provide a significantly large number of irradiated mice that survived for return to the United States for duration-of-life observation. The results of this study, as of 1 December 1951, are given in Appendix B. The effort required to obtain these results was considerable. Since the experiment served as a cross check on the mouse dosimeter study, and since it provided information on the nature of the lethal process, the effort was justified. It is apparent now that physiological and radiological conditions within the cylindrical units were less favorable than in the hemispherical units. If the experiment were to be repeated, the latter units should be used.

There does not seem to be any good reasons for repeating a gamma-ray dose-mortality study using mice, or other small laboratory mammals, at future weapons tests. It has been proved that the biological effectiveness of the gamma radiation is of the same order as that of 250- to 2,000-KVP X rays. In fact the RBE is approximately unity. It is quite unlikely that any significant information could be obtained in a field test, which could not be obtained more easily and more reliably in the laboratory.

3.4 PRODUCTION OF CHROMOSOMAL ABERRATIONS IN *TRADESCANTIA* (PROJECT 2.5.5.1)

Biological dosimetry using *Tradescantia* was based on the fact that there is a quantitative relationship between the dose of radiation applied to the plant and the number of chromosomes damaged after exposure. The biological effect of radiation on *Tradescantia* has been studied extensively, and such studies have provided substantial support to the target theory of the action of ionizing radiation. The response of the plants has been found to be independent of X- or gamma-ray energy over a wide range (approximately 50 to 500 kv), and relatively independent of intensity over the range 5 to 500 r/min. With neutrons, the yield of chromosomal aberrations is inversely related to the energy of the fast neutrons used. In practice it is customary to score the chromosomal aberrations resulting from a given dose in at least 100 cells. The resulting data can be submitted to statistical analysis and confidence limits established. The results of a control study which illustrate

the reliability of *Tradescantia* as a dosimeter are given in Table 3.5. Flower buds were selected from the greenhouse and used in a dry run of Dog Shot. After the dry run, they were exposed to 100 and 135 r of 230-KVP X rays. The estimated dose was then read from the calibration curves obtained at Oak Ridge.

The frequency of aberrations due to gamma or X radiation is given by:

$$y=a+bx, \text{ for one-hit effects,} \qquad (3.10)$$

and

$$\sqrt{y}=a+bx, \text{ for two-hit effects,}$$

where y is the frequency of aberrations, and x is the dose of radiation.

When *Tradescantia* is used as a dosimeter, its useful range extends from approximately 10 to 600 rep. At higher doses damage to the plant cells is so severe that the majority of the cells die before the 24- and 96-hr time of observation. It was originally planned to place *Tradescantia* in drone aircraft and in all stations where appropriate doses were expected. Such complete coverage was not possible for the following reasons:

1. *Tradescantia* did not grow as well at Eniwetok as was expected. This was attributed to the small difference between day and night temperature. Some of the plants were placed in a cool air-conditioned room at night, but these did no better than the ones left in the greenhouse. As a result, the number of plants available at shot time was smaller than anticipated.

2. Approximately half the plants were destroyed by two unforeseeable accidents. The first occurred when a liaison plane crashed directly on the greenhouse shortly before Dog Shot. The second occurred between Easy and George Shots when Japtan was sprayed with DDT and "Lindane" to control flies. Some of the insecticide was blown into the greenhouse with disastrous effects.

3. The number of plants that could be studied was restricted by the number of personnel available to prepare slides and perform the tedious scoring of the aberrations.

At the time of the field test the decision was made to place the plants in all the aircraft and only in the most distant ground stations. This proved to be a wise choice particularly in the case of neutrons, the flux of which was much greater than predicted. Since *Tradescantia* is sensitive to small doses of gamma rays and neutrons, there was little risk of failure to obtain usable data.

Two separate estimates of dose were obtained from each experiment. One estimate was based upon one-hit aberrations which consisted principally of deletions, *i.e.*, the disappearance or dislocation of a portion of a chromosome. Using gamma or X rays, injuries of this sort increase in frequency linearly with the dose and are independent of intensity. The second estimate was based on two-hit aberrations which consisted principally of exchanges of chromosomal material either between the portions of the affected unit or between individual chromosomes. Aberrations of this sort increase as a power of the dose and are somewhat dependent on intensity, or dose rate. With neutrons, exchanges increase

TABLE 3.5 CONTROL STUDY OF *TRADESCANTIA* AT ENIWETOK

TREATMENT	NUMBER OF CELLS EXAMINED	FRACTION NORMAL	CHROMOSOMAL DELETIONS PER CELL	ESTIMATED DOSE	
				r	90 per cent Confidence Interval
None	122	1.00		...	
None	361	0.99	0.008	...	
Specific control[a]	313	1.00		...	
Specific control+100 r, X rays[b]	200	0.78	0.14	107	68–147
Specific control+135 r, X rays	246	0.72	0.175	127	87–165

[a] In the specific control experiment, flower buds were cut, packed, transported to another island, placed in an exposure container and then recovered in the course of a dry run for a shot.
[b] 230-KVP X rays.

linearly with dose and are independent of intensity. In most instances the estimates of dose based on two-hit aberrations are larger than when the one-hit type is used. The latter type, however, are usually the more reliable, and they have been used as the basis for most of the comparison of dose estimates obtained by the various methods. When *Tradescantia* is used as a dosimeter, it is obviously advantageous to employ the aberrations whose yield is a linear function of dose.

3.4.1 Results on Dog Shot

Units of *Tradescantia* were not placed in any of the aluminum-domed stations for Dog Shot for the reasons mentioned above. The plants were placed in all of the eight lead-domed hemisphere stations where the effects of neutrons were studied. Satisfactory preparations were obtained only from the three most distant stations. At the others the dose of neutrons was either lethal or produced such a severe effect that the aberrations could not be scored properly. The results from both Dog and Easy Shots are shown in Table 3.6. The control study of the effect of neutrons was performed at Oak Ridge National Laboratory, using fast neutrons from uranium fission. The dose was expressed in n units, which are reported to represent 2.0 to 2.5 rep/n. In the field experiment neutrons were not measured in n units, but by means of threshold detectors. As pointed out in Sec. 3.2.6, it is proper to use the data for sulfur neutrons outside the lead shield as a relative index of the fast-neutron dose inside. These values are entered in Table 3.6, as well as the estimate of dose in roentgens equivalent man, obtained with the mouse thymus dosimeter system.

TABLE 3.6 BIOLOGICAL ESTIMATES OF NEUTRON DOSE USING *TRADESCANTIA*, DOG AND EASY SHOTS

STATION NO.	DISTANCE FROM ZERO (yd)	SULFUR NEUTRONS[a] OUTSIDE SHIELD	BIOLOGICAL ESTIMATE OF DOSE[b]	
			Mouse Thymus (rem)	*Tradescantia*[c] (n units)
Dog				
73h	1,300	1.7×10^{9}	117	6.0
g	1,200	3.2×10^{9}	201	16.8
e	1,100	6.0×10^{9}	328	31.6
Easy				
85 f	1,300	2.0×10^{9}	...	10.0
e	1,100	4.0×10^{9}	...	27.5
73 h	1,000	1.5×10^{10}	560	47.9
85 d	975	2.0×10^{10}	...	61.6

[a] Only those neutrons with energies of 3 Mev or greater.
[b] Inside 7-in. lead shields.
[c] From exchanges.

3.4.2 Results on Easy Shot

Gamma rays. Units of *Tradescantia* were placed at seven different distances from zero, either in the cylindrical stations of the 70, 71 series, or in aluminum-domed hemispheres. Preparations suitable for scoring were obtained from all seven locations. The results obtained are shown in Fig. 3.9. The estimates of dose, in roentgens, are based on one-hit aberrations (deletions) observed 21 to 24 hr, or 4 days after irradiation. Other curves in this figure represent the dose estimates obtained with film packs, ionization chambers, and the mouse thymus system.

Neutrons. Satisfactory data were obtained from plants exposed in four lead-domed hemispheres. The results, expressed in n units, are given in Table 3.6 and shown graphically in Fig. 3.10. In this graph, the value for n is based on exchanges rather than deletions. Since the effect of neutrons varies linearly with dose, regardless of the type of aberration under study, it is quite proper to estimate dose in this way. The slides obtained after Easy Shot were of poor quality and the scoring of deletions was not considered reliable. In Fig. 3.10, the results obtained at Dog and Easy Shots are plotted on the same scale. In both cases the neutron flux, measured biologically, decreases as a power of the distance in the range 975 to 1,300 yd. On Easy Shot the neutron flux at comparable distances was about equal to that on Dog Shot although the weapon yields differed by a factor of approximately 2. The difference in slope of the two lines is not significant.

3.4.3 Results on George Shot

At George Shot, *Tradescantia* was exposed in both types of stations. None of the preparations were satisfactory and no estimates of

dose can be given. It is not certain that this effect was entirely the result of high dosage, since the plants had been damaged by insecticide spraying a few days before the shot.

3.4.4 Results in Drone Aircraft

For exposure in the drone aircraft, the flower buds were placed in corked Dewar flasks filled with chipped ice. This was necessary since control studies had shown that the yield of chromosomal aberrations was affected by the temperature at the time of irradiation. Since each drone aircraft made its cloud pass at a different altitude, it was more convenient to have all plants at one temperature than to make the necessary extrapolation. The control data for this experiment were obtained under conditions which simulated the pressure and temperature of the field test. Unfortunately, the source of radiation was cobalt^{60}, and the intensity was 4.6 r/min. The intensity of the radiation was much greater in the drones which traversed the cloud in 10 to 30 sec and was of the order of 300 to 500 r/min. For this reason, the dose estimates are based upon one-hit aberrations (deletions) the yield of which is independent of intensity. The results obtained in the drones on three shots are given in Table 3.7, along with dose estimates from the film packs and from the mouse thymus dosimeters. The agreement between the *Tradescantia* and film is generally better than the agreement between either of these and the mouse thymus system. The only plausible explanation for the discrepancies that are evident in the tabulation is that all values are at or below the lower limit of measurement of the mouse thymus system.

3.4.5 Evaluation

Tradescantia, as used in the 1951 field tests, was an adequate biological dosimeter. There is good general agreement between estimates of dose of gamma radiation obtained with the plants, and with the other biological and physical dosimeters. When the biological effectiveness of the gamma rays of the bomb is compared to that of X rays, the RBE is found to be approximately unity. The special value of *Tradescantia* in this study is related to the known characteristics of the response of its chromosomes to radiation. When dose estimates are based on the appropriate type of chromosomal aberration, it is possible to use a biological system whose response is independent of energy and intensity over a wide range. Although it cannot be stated with certainty, it is probable that the nuclear gamma radiations were either included within this range, or were not far outside it. The technique of measuring the effect of any radiation on *Tradescantia* chromosomes is essentially statistical, and the error of estimate is determinable with one important qualification: the detection of aberrations, and their correct interpretation requires a high degree of competence in cytology, and is subject to a considerable human error. For this reason, the results are stated with fiducial limits at the 90 per cent level of confidence.

The results of the attempt to measure neutrons are difficult to evaluate. Using fast neutrons from various cyclotrons, it has been

TABLE 3.7 ESTIMATES OF GAMMA-RAY DOSE IN DRONE AIRCRAFT

ALTITUDE (ft)	DOG SHOT DOSE (r)			EASY SHOT DOSE (r)			GEORGE SHOT DOSE (r)		
	Trades.[a]	NBS Film	Mouse[b]	*Trades.*	NBS Film	Mouse	*Trades.*	NBS Film	Mouse
16,000	117	112	137	34	36	<75	8	5	<75
18,000	71	66	115	73	54	79	12	11	87
20,000	78	80	165	178	135	171	16	18	120

NOTE: See also Chap. 8 of this section.

[a] Based on one-hit deletions.

[b] Average values.

shown that the yield of aberrations is inversely related to energy. The calibration of *Tradescantia* for the field test was performed with fast neutrons from uranium fission in the Oak Ridge pile. The neutrons from these sources had an average energy of 1.0 Mev and a maximum energy of 4.0 Mev. No data are available for the comparison of the spectrum of the neutron population inside the lead-domed hemispheres with those from the pile. In the case of the mouse thymus dosimeters, it was inferred that the majority of the biological effect was due to fast neutrons (in excess of 1 Mev); but it is not possible to make a similar inference for *Tradescantia*. The calibration of the plants was done in terms of n units, using a 100-r Victoreen thimble ionization chamber, but no such measurement was made in the field. The field data, then, can only indicate the relative dose of neutrons at various distances from zero. From the biological point of view, this information is practically meaningless, and it cannot be used to amplify or interpret the results obtained with the mice. The data may be used to make a crude comparison of the relative neutron flux from two weapons, such as Dog and Easy.

The *Tradescantia* method is difficult to apply, and the results may be compromised by many factors, not all of which are foreseeable or controllable. The plants are delicate, and did not grow well in the unfamiliar environment of Eniwetok. On the basis of cost, *Tradescantia* was less expensive than the mice. For the measurement of gamma radiation as a function of distance, the NBS calibrated film packs gave comparable results and were more dependable than the plants. The measurement of neutron dose was not practical, since the results could not be interpreted. There is little reason to believe that additional control studies, or a different experimental design would overcome the inherent difficulty of using *Tradescantia* as a neutron dosimeter. There does not appear to be any good reason to use *Tradescantia* as biological dosimeters in future field tests of nuclear weapons.

3.5 MUTATION RATE IN *GLOMERELLA* (PROJECT 2.5.5.2)[12]

The mould *Glomerella* was used in an attempt to measure dose biologically at the stations of the 84 series located 300 to 900 yd from Easy zero. (See Section 1, Table 3.5 and Fig. 4.9.) At this distance the nuclear radiation is a mixture of neutrons and gamma rays, the physical dosimetry of which is a problem. The biological effects of radiation on *Glomerella* can be measured in terms of the survival rate and the mutation rate. Relatively large doses of X rays or neutrons are tolerated and the determination of the effect is comparatively simple. For the 1951 field test, *Glomerella* was calibrated by exposure to fast neutrons in the pile at Oak Ridge. In Fig. 3.11 are given curves for per cent mutations and the log of the fraction of spores surviving as functions of fast-neutron dose in roentgens equivalent physical. The results of the field experiment are indicated on these curves by station number and the "equivalent dose" of fast neutrons can be read from the abscissa. The estimates of dose, using survival of *Glomerella* spores, are compared in Table 3.8 with the readings of the Vycor glass dosimeters. The values at the distant stations are in good agreement. This is surprising in view of the different methods of calibration, and the lack of knowledge regarding the biological effectiveness of various radiations for *Glomerella*. It is probable that the agreement is fortuitous. The field experiment, however, provided a large amount of material for the study of radiation-induced mutations. *Glomerella* is not recommended as a biological dosimeter unless a more comparable method of calibration can be found.

3.6 EXPOSURE OF CORN SEED (PROJECT 2.5.5.3)

Corn seed was exposed to the mixed radiations of Easy Shot in the stations of the 84 series. After the test, the corn was planted and the dose estimated on the basis of abnormalities of seedling growth. The control seeds

[12] Greenhouse Report, Annex 2.10.

TABLE 3.8 COMPARISON OF DOSE ESTIMATES USING *GLOMERELLA* AND VYCOR GLASS

STATION NO.	DISTANCE (yd)	ESTIMATE OF DOSE (10^3 r)	
		Glomerella	Vycor[a]
84a	300	...	3,000
b	400	...	1,080
c	500	220	292
d	650	97	93
e	725	55	39
f	800	45	22

[a] Calibrated against gamma rays of cobalt^{60}; dose estimate based on densitometry. Nothing is known about the response of Vycor to neutrons.

were exposed to slow neutrons and X rays. The samples of corn from Eniwetok were properly graded with respect to the relative dose of radiation that they had received. It was possible, by means of side-to-side comparisons, to pair up cultures of corn exposed to Easy Shot and those that received the control irradiations. Unfortunately, there is so much uncertainty regarding the absolute doses given the controls that no good estimate of dose in the field is possible. It is obvious that corn seed can be used to make gross estimates of dose in the high-dosage range if properly calibrated against an appropriate source. It is equally obvious that the techniques are time-consuming and not very accurate.

3.7 EVALUATION OF BIOLOGICAL DOSIMETERS

Five biological systems were studied in an attempt to measure the dose of gamma rays and neutrons in terms of the biological effect produced. Fundamentally, the accuracy of a biological dosimeter for use with nuclear weapons depends upon two factors: (1) the accuracy of the physical methods used for calibration, and (2) the reliability of the biological system.

The dosimetry of gamma rays that was performed with mice and *Tradescantia* employed systems which had been carefully calibrated using reproducible sources and accurate physical dosimeters. The error of estimate of any value for dose received in the field test was certainly not greater than 15 per cent except for the neutron estimates using *Tradescantia*. When a series of data are used to construct a curve, such as Figs. 3.6 or 3.8, the point-to-point variance is considerably less than 15 per cent as can be shown by the least-squares fittings reported in the annexes. The results obtained using mice and *Tradescantia* were consistent among themselves. Estimates of dose of gamma rays in roentgens equivalent man at any distance where all three methods could be compared seldom differed by more than 15 per cent. This reliability is as good as is claimed for the NBS film calibrated at 600 kv. For higher energies, the error in the film is greater than 15 per cent. The reliability of gamma-ray dose estimates using the mouse thymus system was demonstrated in another way. The data were used to calculate the mean free path of the gamma-ray photons and to scale the yield of three of the weapons. The results obtained from these calculations were in good agreement with the values obtained by accepted physical measurements. It can be concluded, therefore, that it is possible in a field test to use mice and *Tradescantia* as biological dosimeters, the reliability of which is equal to that of NBS film packs and ionization chambers. Only very crude data were obtained when *Glomerella* and corn seed were used to estimate dose. All the biological dosimeters were difficult and expensive to operate, and the results obtained with them, in the case of the gamma radiation, can be reproduced simply and relatively cheaply with physical methods, such as film and ionization chambers.

The situation was different in the case of neutron measurements. The biological dosimeters (mice and *Tradescantia*) gave an integrated value for dose which could not be obtained from the threshold detectors, or from other physical methods used. The values for dose determined using mice were expressed in roentgens equivalent man, but it was not possible to translate this directly into either roentgens equivalent physical or flux on the basis of existing information. The values for dose determined with *Tradescantia* were expressed in n units, but these could not be translated into either roentgens equivalent man, roentgens equivalent physical, or flux. It ap-

pears that mice can be used to advantage to measure neutron dose particularly in shielding situations where moderation of fast neutrons is occurring. Without being able to interpret, or to correctly evaluate neutron dose measured biologically in terms of roentgens equivalent physical or flux, it is reasonable to believe that the magnitude of the biological effect inside the lead shields was measured in terms of biological equivalents of 230-KVP X rays with the same degree of accuracy as in the case of mice exposed to gamma rays.

The biological effectiveness of the gamma radiation was readily calculated from the mouse data. When this value was compared with estimates of the biological effectiveness of X rays generated at energies ranging from 230 to 2,000 KVP, it was shown that the ratio was essentially unity. The extremes of comparison ranged from 0.7 to 1.0. Differences of this amount are of no consequence biologically. There is good reason to believe from the data on survival rate and mortality rate that the lethal biological action of the gamma radiation of the weapon was the same as that of ordinary hard X rays. The demonstration that the RBE for mice is approximately unity (compared with X rays) is very important and should provide a reliable answer to speculations concerning the possible influence of high intensity, high energy, and broad spectrum on the biological effect of atomic bomb gamma rays.

The data obtained with *Tradescantia* confirm this conclusion. In the range of dose and intensity in which the plants were exposed and using the one-hit aberrations as the basis of estimate, it is known that the response of *Tradescantia* is independent of intensity. None of the control studies employed radiation with an effective energy or spectrum equal to that of the nuclear radiation. The good agreement between dose estimates made using the plants and physical dosimeters, however, indicate that in this case also the RBE was approximately unity.

It was possible using the mouse thymus system, to measure in roentgens equivalent man the biological effect of the bomb neutrons behind 7 in. of lead shielding as a function of distance from zero. By calculation it was possible also to estimate roentgens equivalent man outside the shield.

3.8 CONCLUSIONS

The significance of the foregoing results can be summarized as follows:

1. Mice and *Tradescantia* can be used as effective biological dosimeters for gamma rays.
2. The results of gamma-ray measurements made with physical and biological dosimeters are the same within the error of the respective methods.
3. It should not be necessary at future tests to use biological dosimeters to measure gamma rays.
4. The RBE for gamma rays from a nuclear weapon is unity compared with ordinarily available hard X rays. In radiobiological research, X rays generated at energies ranging from 230 to 2,000 KVP are acceptable substitutes for a nuclear weapon.
5. Mice may be useful as biological dosimeters for neutrons. It seems unlikely that *Tradescantia* can be relied upon for this purpose.
6. The integrated biological effect of bomb neutrons behind shields can be measured more effectively with mice than with available physical methods.
7. It was not possible to determine the RBE for specific spectral components of the neutron flux because of the inadequacy of both physical spectral measurements and laboratory biological data.
8. Corn and *Glomerella* are not satisfactory dosimeters for field use until adequate calibration with an appropriate source has been accomplished. Their utility for such is, however, open to question.

Chapter 4

Quality of the Gamma Radiation (Project 2.4.4)

4.1 INTRODUCTION

The quality, or the hardness, of the gamma radiation emitted by a nuclear weapon is of interest for three principal reasons:

1. For the design of collective shielding, such as air-raid shelters, and for the design of individual or personnel shielding, such as body armor.

2. For the conduct of laboratory experiments on man or large mammals to evaluate the therapeutic or protective agents or fundamental laboratory studies regarding the properties and effects of atomic bomb radiations.

3. For the interpretation of clinical data, such as the occurrence of epilation.

Principally on the basis of the absorption coefficient of air, the effective energy of the gamma rays is reported to be approximately 3 Mev.[1] Some workers have inferred that the value should be much lower, and estimates of the order of several hundred thousand electron volts have been discussed. Prior to the 1951 tests, no attempt had been made to determine the effective energy in unit-density, or tissue-equivalent material.[2] Such a measurement was obviously desirable for the reasons cited above. The important elements in the present experiments were the radiation detectors and the phantoms which will be considerd separately.

[1] *Greenhouse Handbook of Nuclear Explosions,* Scientific Director's Report of Atomic Weapon Tests at Eniwetok, 1951, Volume III, Part I (1951).

[2] "Effective energy" is used in radiology to designate the energy of monochromatic X rays or gamma rays which have the same absorption in the specified material as the radiation under consideration. The concept originated with Duane.

4.2 RADIATION DETECTORS

The most useful detector was the Sievert ionization chamber, the operating characteristics of which are described in another report.[3] The chambers functioned in a most satisfactory manner in spite of the tropical climate at Eniwetok. Recalibration after the tests gave results that were substantially the same as those obtained in pre-test studies. The chambers were placed in the aluminum-domed hemispherical units for Dog Shot, and in the spherical lucite phantoms for Easy and George Shots. It was concluded that they were reliable dosimeters for use in phantoms, even under field conditions.

The film packages [4] placed in the phantoms were not satisfactory since the film was energy-dependent for the longer wave lengths. This is demonstrated in Fig. 4.1, where increasing thicknesses of the lucite spherical phantoms resulted in an increase of film density. These results were obtained with a series of doses of 2,000-KVP X rays. Similar results were obtained with the phosphor glass and the activated potassium iodide crystals. For all practical purposes the readings of all the detectors inside phantoms, except the ionization chambers, can be disregarded.

4.3 PHANTOMS

The spherical lucite phantoms were quite satisfactory. The closest station for Easy Shot, Station 81, located at 900 yd, was dam-

[3] Greenhouse Report, Annex 2.4, Part II.

[4] These should be clearly distinguished from the NBS film packs. The same four films were used in each, but the package did not contain the lead, tin, and bakelite absorbers.

aged by flying debris and the spheres and detectors were lost. Two stations on Easy Shot contained a full set of ionization chambers in each of the seven spheres: Station 80c at 1,460 yd, and Station 80d at 1,645 yd. (See Section 1, Table 3.2 and Fig. 4.9.) All the spheres were recovered and all the chambers gave satisfactory readings. The other two spherical phantom stations on Easy Shot contained film and phosphor glass detectors, the readings of which were unsatisfactory. On George Shot, only two spherical phantom stations were used, and the closer one, Station 80c at 1,800 yd, was demolished by flying debris or blast. (See Section 1, Table 3.3 and Fig. 4.11.) The results of the experiment using the spherical phantoms would have been more satisfactory if spheres with wall thicknesses greater than 17.5 cm had been used. Such large spheres were not available, however, until the fall of 1951.

The mouse, swine, and tank phantoms were all recovered without incident. Since all contained energy-dependent detectors, the results were disappointing.

4.4 RESULTS

Spherical Phantoms. The readings of the ionization chambers in the seven spherical phantoms at each of the three satisfactory stations are plotted in Fig. 4.2. The curves have a similar shape and can be combined. When this is done (Fig. 4.2), the readings in the spheres with a 0.5-cm wall thickness are taken as 100 per cent of the air dose. The per cent of the air dose, or the depth dose, is then decreased to 65 per cent in the thickest spheres with walls 17.5 cm thick. The maximum variation of the dose measured in any thickness of lucite when normalized was ± 1.5 per cent. These data can be used to calculate the mean free path of the gamma-ray photons in air and lucite. The absorption coefficient, μ, in lucite is 0.03046 cm^{-1}, and the mean free path ($\lambda = 1/\mu$) is 32.8 cm. The density of the lucite used was 1.17 g/cm^3. Assuming that the density of air at shot time was 0.001154 g/cm^3, the mean free path of the effective beam was 364 yd, a value which is in good agreement with the biological and other physical measurements. The curves are of interest since there is no variation in the dose reading until spheres with wall thicknesses greater than 3.0 cm are examined. This indicates that the gamma radiation is in equilibrium in air, and hence in lucite. The effective energy of X rays or gamma rays which correspond to these values is discussed below.

Swine and Mouse Phantoms. Variations of density were observed in the films placed at different positions within the swine phantoms and in the mouse tray assemblies. Sufficient uncertainty is attached to these readings to justify their elimination from this report. The average values for all the film in a single phantom agreed reasonably well with the readings of the NBS film packs in the same geometry.

Tank Phantoms. Information on depth dose could not be obtained from the tank phantoms because of the characteristics of the film. The average readings, however, gave a reliable value for the gamma-ray dose delivered to the position occupied by the phantom. The values were all lower than the dose measured in air at the same distance. The discrepancy is due to the variable shielding afforded by the armor, machinery, etc., of the tank.

4.5 QUALITY OF THE GAMMA RADIATION

The quality, or effective energy, of the gamma radiation was estimated by exposing the series of seven spherical phantoms to various sources of X rays and gamma rays. It was assumed that the source whose radiation duplicated the depth-dose curve obtained in the field test, had the same effective energy. The results of this experiment are shown in Fig. 4.3. It can be seen that the gamma rays of cobalt^{60}, and heavily filtered 2,000-KVP X rays were less energetic, and that X rays from the 22-Mev betatron were more energetic than the bomb radiation. The X rays from a General Electric 10-Mev betatron, without added filtration, duplicated the results obtained at Eniwetok. This same betatron was used in one calibration of the NBS film packs, and the spectrum of its beam is now being studied by the National Bureau of Standards. It is the con-

vention to assume that the effective energy of the X radiation from a betatron is approximately one-third the maximum energy. It is concluded from the study with spherical phantoms containing ionization chambers that the effective energy of the gamma radiation of a nuclear weapon at 1,400 to 2,100 yd is approximately 3.3 Mev. In future studies thicker spheres will be used to carry the per cent depth-dose measurements below 50 per cent.

4.6 EVALUATION

Except for the results obtained with the three groups of lucite spherical phantoms containing ionization chambers, the attempt to measure depth dose in unit-density material was unrewarding. The three good stations provided a reliable composite curve of depth dose in lucite. The results demonstrated that there was no detectable difference between the effective energy at 1,460 and 1,645 yd on Easy Shot. There was also no difference between the single curve obtained at 2,160 yd on George Shot, and the two measurements on Easy. It is not possible to extrapolate the effects observed at the two points on Easy Shot to other distances from zero. However, the range in which the observations were made includes the distance at which the effects of biomedical interest occur.

The concept of effective energy was developed by Duane and is regularly used by radiologists to specify the quality of a beam of radiation. The determination of effective energy is entirely empirical, and it is not easy to extrapolate from one absorbing material to another of different density. Effective energy should be clearly distinguished from average energy, since the former term carries no implication of the spectral distribution of the beam. It is, however, a simple and acceptable basis for comparing radiation from several sources. A knowledge of the effective energy is useful for planning shielding of various sorts. It is also useful for laboratory experiments involving shielding, since it permits the worker to use a source which is comparable to nuclear radiation in this respect at least. Experiments using large animals or human subjects would be of most significance if the depth dose of the laboratory source resembled closely or duplicated the depth dose of the weapon radiation. Using the data obtained in the 1951 tests, it should be possible to design and build X-ray equipment for large animal studies that is an acceptable substitute for the bomb.

This study does not contribute any new information for the evaluation of the occurrence of epilation in the Japanese. It has been suggested that the soft component of the bomb radiation was sufficient to produce epilation when the total dose was not fatal. The depth-dose experiments neither support nor contradict this assumption.

Another useful application of the depth-dose study is to provide the basis for the calibration of film and other dosimeters for use in future weapons tests, or as personnel dosimeters. On the basis of these results, it would be appropriate to calibrate all such instruments using the 10-Mev betatron or an equivalent source. The film used in the NBS film packs by Program 1 was calibrated with the betatron, as well as with sources of lower energy. The calibration chosen for use at Greenhouse was obtained with X rays of 600-kv effective energy. In the range of biological interest, the readings of the film packs can be corrected by a multiplication factor of approximately 1.25, which represents the difference in density resulting from the greater effective energy.

4.7 CONCLUSIONS

1. The Sievert miniature ionization chamber is a reliable detector for measurement of the dose of gamma radiation of a nuclear weapon.

2. The spherical lucite phantoms with wall thicknesses ranging from 0.5 to 17.5 cm (or greater) can be used to specify the quality of the beam of gamma radiation from a nuclear explosion. The HVL in lucite is greater than 17.5 cm.

3. The effective energy of the gamma radiation is approximately 3.3 Mev and is accurately duplicated by the 10-Mev betatron without added filtration.

4. Gamma rays of cobalt^{60}, and filtered supervoltage X rays are acceptable substitutes for radiation experiments using large mammals.

Chapter 5

Median Lethal Dose for Large Animals (Projects 2.4.1.4 and 2.4.1.5)

5.1 INTRODUCTION

The dose-mortality response of swine and dogs was investigated to gain additional information on the probable value of the median lethal dose (MLD or LD_{50}) of man, and to provide a basis for comparison with laboratory studies. The design of each experiment was identical. Ten dogs and ten pigs were placed in each of nine stations at distances ranging from 1,354 to 1,750 yd from Easy zero. (See Section 1, Table 3.1 and Fig. 4.9.) The stations consisted of nine double-cylinder units, the features of which are described in another report.[1] In spite of the considerable logistical problem involved in moving these animals 18 miles by water, all were placed and recovered without incident. The details of the experiments are described in the appropriate annexes.[2] One series of control studies was conducted using bilateral 2,000-KVP X rays at the Naval Medical Research Institute. Another series of controls was studied at the Naval Radiological Defense Laboratory using bilateral 1,000-KVP X rays. The animals in the Naval Radiological Defense Laboratory series were subjected to an environmental stress simulating that which was expected at Eniwetok. The details of these experiments are given in another report.[3] The results obtained at the Naval Radiological Defense Laboratory were the most suitable for comparison with the field data.

The locations of the stations were chosen on the basis of a predicted yield for Easy Shot which varied from 40 to 60 kt. It was hoped that at least one station would have no mortality, and that at least three or four would have fractional mortality. Predictions of the LD_{50} varied, but in general they were too high. The number of stations and the number of animals per station were established in consultation with biometricians. It was hoped to determine the distance at which the LD_{50} was received with sufficient accuracy that the range of the 95 per cent confidence interval would be no greater than 100 yd. The planning of the experiment was based on this requirement. The control studies at the Naval Radiological Defense Laboratory were similar with respect to the design of the experiments.

After exposure the animals were examined several times daily until death occurred. A complete autopsy was performed soon after death, and on the 31st day after irradiation the survivors were killed and autopsied. Serial blood samples were drawn from some of the dogs, and were used for hematological and biochemical studies, which are discussed in Chap. 6. There was a difference of opinion among the observers regarding the effect of the daily bleeding. The Director of the biomedical program did not believe that it was deleterious, but the project officer did. The collection of blood samples was discontinued in the 16th day of the experiment.

5.2 RESULTS WITH SWINE

The results of the swine experiment are displayed most concisely in graphic and tabular form. In Table 5.1 values are given for the $LD_{50/30}$ for the field and the various control studies. In the case of the swine exposed to

[1] Greenhouse Report, Annex 2.3.
[2] Greenhouse Report, Annex 2.5, Parts II and III.
[3] Annex 2.2, Part VI.

Easy Shot, the LD_{50} was 231 r, which was delivered at 1,705 yd. The 95 per cent confidence interval extended from 200 to 250 r. In terms of distance, this range is equal to approximately 60 yd. The dose-mortality curve for the field study is given in Fig. 5.1.

5.3 RESULTS WITH DOGS

The results of the dog experiments are also displayed in graphic and tabular form. Table 5.2 contains the values for the $LD_{50/30}$ for the field and the control studies. For the dogs exposed to Easy Shot, the LD_{50} was 270 r, which was delivered at 1,664 yd. The 95 per cent confidence interval extended from 238 to 309 r. In terms of distance, this range is equivalent to 80 yd. The dose-mortality curve for the field test study is given in Fig. 5.2.

5.4 EVALUATION

The distance from zero at which the MLD was delivered was greater than had been anticipated. It was fortunate that Station 72i was provided at 1,750 yd, otherwise it would have been difficult or impossible to interpret the results. It was also fortunate that the yield of Easy Shot was not greater than 48 kt. The use of probit analysis permitted a valid treatment of the data in spite of the fact that there were survivors in only the two most distant swine stations and the three most distant dog stations. For the field data, the fiducial limits for 95 per cent confidence, expressed in yards, were smaller than the value of 100 yd which was specified when the experiment was designed.

The behavior of the animals, considered by dose groups, was quite consistent, and there is no reason to suspect that bias, bad sampling, or unrecognized complications affected the results. It is believed that the values for MLD ($LD_{50/30}$) for swine and dogs are reliable within the limits of the 95 per cent confidence interval.

In Tables 5.1 and 5.2, the results of the field and control experiments are arranged in the order of increasing values for the LD_{50}. Since the experiments were conducted in a comparable manner, it is necessary to inquire into the reasons for the differences. In Table 5.2, the results of two other dose-mortality studies us-

TABLE 5.1 ANALYSIS OF SWINE MORTALITY DATA

EXPERIMENT	NUMBER OF PIGS	LD_{50} (r)	LOG LD_{50}	FIDUCIAL LIMITS, 95 PER CENT CONFIDENCE (r)
Easy Shot	90	230		200–250
NRDL controls environmental stress	58	386	2.587 ± 0.054	303–493
All NRDL controls	118	425	2.622 ± 0.037	355–495
NRDL controls no stress	60	453	2.656 ± 0.050	362–566

TABLE 5.2 ANALYSIS OF DOG MORTALITY DATA

EXPERIMENT	NUMBER OF DOGS	LD_{50} (r)	LOG LD_{50}	FIDUCIAL LIMITS, 95 PER CENT CONFIDENCE (r)
U of Chicago[a]		250		
Easy Shot	90	270		238–309
NRDL controls no stress	64	305	2.485 ± 0.019	278–333
All NRDL controls	130	309	2.490 ± 0.015	289–330
NRDL controls environmental stress	66	313	2.496 ± 0.023	283–348
U of Rochester[b]		330		

[a] Personal communication, J. G. Allen.
[b] Reported in AR–124, Boche and Bishop, 1946.

ing dogs are included for comparison. The physical characteristics of the various sources of radiation which may be important are listed in Table 5.3. For the purpose of this tabulation it has been assumed that the density of masonite and lucite phantoms is the same. It can be seen that there is an inverse relationship between the LD_{50} and the per cent depth dose. At 17.5 cm (the depth dose at 17.5 cm was chosen since it is the lowest value obtained for the bomb's gamma rays) there is also an inverse relationship between the effective energy and the LD_{50}. In the case of the swine, the difference between the MLD at Easy Shot and the control MLD was greater than occurred with the dogs. It is probable that the disparity is due to the greater weight and the larger volume of the pigs.

The low values for the $LD_{50/30}$ obtained at Easy Shot are explained most easily by attributing them to the high effective energy of the gamma radiation. It is reasonable to assume that the more energetic radiation will deliver a greater dose to vulnerable tissues throughout the animal than would occur with a less energetic radiation. This conclusion is supported by the studies of Tullis [4] using swine where the total dose of radiation was delivered either to one side of the animal, or divided and half delivered to each side in turn. When irradiation was bilateral, the LD_{50} was approximately 100 r or 20 per cent lower than when it was unilateral. It should be recognized however that the swine used for Test Easy were smaller and younger than those used for the X-ray control group.

The dose-mortality studies demonstrated that the nuclear radiation was more effective than supervoltage X rays for killing dogs and swine. In the case of the smaller subject, the dog, the gamma rays were 15 per cent more effective than 2,000-KVP X rays. In the case of the larger animals, the gamma rays were 80 per cent more effective. In the absence of evidence to the contrary, it may be assumed that the difference between the two species is due to size alone.

The results of the dose-mortality studies cannot be used to provide reliable estimates of the MLD of men. The average man is larger than the average pig used at Eniwetok. The data suggest that the human LD_{50} could be as low or lower than 230 r. If it was known that the two species were equally radiosensitive, this would be a logical conclusion. The most that can be done with the animal data is to use it as a basis for further experimental studies.

[4] John L. Tullis, C. F. Tessmer, E. P. Cronkite, and F. W. Chambers, Jr., "The Lethal Dose of Total Body X-ray Irradiation in Swine," *Radiology*, LII (1949), 396–400.

TABLE 5.3 PHYSICAL CHARACTERISTICS OF RADIATION USED FOR DOSE-MORTALITY STUDIES OF DOGS AND SWINE

EXPERIMENT	LD_{50} (r)	KVP	HVL		PER CENT DEPTH DOSE AT 17.5 CM, UNIT-DENSITY MATERIAL
			Pb (mm)	Cu (mm)	
Swine, Easy Shot	230			.	65
Swine, NRDL bilateral controls	425	1,000	2.03	.	50
Swine, NMRI bilateral controls	450	2,000	4.3	.	50
Swine, NMRI unilateral controls	550	2,000	4.3	.	50
Dogs, U of C rotated controls	250	250		2	..
Dogs, Easy Shot	270			.	65
Dogs, NRDL bilateral controls	309	1,000	2.03	.	50
Dogs, U of R rotated controls	330	1,000	5.12	.	..

5.5 CONCLUSIONS

1. The $LD_{50/30}$ for pigs exposed to a 48-kt atomic bomb was 230 r. The distance at which this dose was delivered was 1,705 yd.

2. The $LD_{50/30}$ for dogs exposed to a 48-kt weapon was 270 r. The distance at which this dose was delivered was 1,664 yd.

3. For the killing of dogs, the gamma rays were 15 per cent more effective than supervoltage X rays. In the case of the pigs, the gamma rays were 80 per cent more effective.

4. It is not possible to predict the LD_{50} for man on the basis of these data. It is possible, however, that the human MLD may be as low as that of swine.

5. When dogs are used in radiobiological research, supervoltage X rays, or the gamma ray of cobalt^{60} should be acceptable substitutes for the gamma radiation of an atomic bomb.

Chapter 6

Clinical Pathological Studies (Projects 2.4.1.2, 2.4.1.3, and 2.4.3)

6.1 INTRODUCTION

The term, clinical pathological studies, as used here includes all the observations that were made on pigs and dogs with the exception of the dose-mortality study. In addition to the 90 animals of each species used for the latter, 32 dogs and 32 pigs were exposed in Station 83 at 1,440 yd from Easy zero. These animals were sacrificed serially at intervals over a period of 9 days to study in sequence the development of the pathological lesions that comprise radiation injury. The broad objective of all these studies was to examine large animals exposed to an atomic bomb under controlled conditions. The clinical material obtained at Hiroshima, Nagasaki, and Bikini was unsatisfactory in many respects due to circumstances beyond the control of the investigators. It was hoped that the present study would complement the earlier ones and remedy some of the deficiencies in our knowledge of the medical effects of gamma radiation from an atomic bomb.

6.2 PATHOLOGY IN SWINE AND DOGS

Complete autopsies were performed on the 122 pigs and the 134 dogs exposed to Easy Shot. Fresh gross specimens were photographed in color and excellent pictures were obtained for teaching purposes. Particular attention was devoted to the time of appearance of evidence of radiation injury in the gastrointestinal tract, lymphatic apparatus, hematopoietic system, and the gonads. The serial study revealed the extent of the pathological processes before the occurrence of complicating hemorrhage and bacteremia. Material of this sort was not available for study at Bikini or in Japan. A detailed illustrated description of the pathological lesions, and a comparison with similar specimens exposed to X rays is given in another report.[1] No serious difficulties occurred in the course of the field study, and all of the histological specimens and the photographs were returned safely to the United States.

6.3 EVALUATION OF THE PATHOLOGY STUDY

An important objective of the pathology studies was to compare the character, sequence, and extent of the typical lesions in animals exposed to similar doses of gamma rays from the bomb, and supervoltage X rays. This was done for two reasons. First, it was believed that any significant difference in the pathogenesis of the two types of radiation injury might be discovered in the serial study. Second, it was hoped that careful repeated examinations of animals irradiated under controlled conditions might yield clues to the pathogenesis which could be exploited to advantage. When the results of the field and control studies are examined critically, it is not possible to detect any difference between the pathological findings when animals are compared at the same time after exposure to equivalent doses of X rays and gamma rays. The pathologists described minor differences between the field-test animals and the controls. It is the opinion of the writer that such variations are nonspecific in character,

[1] Greenhouse Report, Annex 2.6, Parts I and II.

and should not be attributed to the quality or the intensity of the nuclear radiation.

The most important result of the pathology study was the unequivocal demonstration of the analogous character of the radiation injury inflicted by atomic bombs and by supervoltage X rays. The careful study of the pigs exposed at Tests Able and Baker at Bikini was restricted to animals that died spontaneously. When these tissues were compared with preparations from pigs killed by supervoltage X rays, no significant differences could be seen. The present study extends these observations to include animals sacrificed at frequent intervals after equivalent exposure to each type of radiation. Dogs have not been exposed at other weapons tests, but there have been a number of careful studies of animals exposed to X rays produced at 250, 1,000, and 2,000 KVP. These studies have included autopsies of animals that died spontaneous deaths and of animals sacrificed serially starting soon after exposure. The findings in the dogs exposed at Operation Greenhouse were the same in every respect as the lesions caused by hard X rays.

One of the remarkable aspects of radiation injury is the consistency of the clinical features and of the autopsy findings. The present study adds two well-controlled experiments to the evidence for the unitary character of the syndrome of whole-body radiation injury. The available evidence clearly demonstrates that when a single whole-body exposure to ionizing radiation is fatal, the clinical symptoms and autopsy findings are the same regardless of the source or quality of the radiation. As a corollary to this, there is no good reason to question the propriety of conducting studies of experimental therapy using proper laboratory sources. These conclusions are important, since they demonstrate that it is not necessary to use an atomic bomb to investigate radiation injury.

An effort was made to obtain animals for pathological study as soon after exposure as possible. The best that could be done was to return four dogs and four pigs to the laboratory approximately 4 hr after the firing of Easy Shot. When these animals were examined, nothing was found that differed in any way from the findings on animals examined at the same time after exposure to X rays. It would be unusual, to say the least, if the pathological processes were shown to be different during the first few hours after irradiation and identical at all times later than that.

6.4 EVALUATION OF CLINICAL PATHOLOGY STUDIES

The studies termed clinical pathology included the following:

1. Daily blood counts on four groups of ten dogs each.

2. Daily measurement of the concentration of serum iron in eight dogs exposed in Station 83.

3. Determination of the pattern of the serum proteins during the first 8 days, using for each sample, a different dog from the group exposed at Station 83.

4. Daily measurement of activity of a vasodepressor material (VDM) in eight dogs exposed at Station 83.

5. Aerobic and anaerobic blood cultures were obtained from each pig and dog in the serial sacrifice study.

The detailed results of these studies are presented in another report.[2] In addition to these five studies, several others, biochemical studies, were undertaken which were not successful. The practice of transporting blood specimens 5,000 to 7,500 miles for analysis is not recommended.

All the results were the same as were found in the control studies, and as described by other investigators of whole-body radiation injury. From the standpoint of evaluation, however, this is considered to be a favorable outcome. In view of the autopsy findings, it is not surprising that the hematological, bacteriological, and biochemical findings were the same in animals exposed to equally lethal doses of gamma rays or hard X rays. This study can be accepted as additional confirmation of the similarity, or the identity, of acute

[2] Greenhouse Report, Annex 2.6, Part III.

whole-body radiation injury regardless of whether it resulted from exposure to an atomic bomb, or was inflicted in the laboratory using hard X rays.

The clinical studies were performed to verify and extend the observations made at Operation Crossroads. The lessons learned at Bikini were applied to advantage in the planning of Operation Greenhouse. The period of preparation for the 1951 tests was sufficiently long that it was possible to perform careful control studies, and develop techniques to minimize variables of many sorts. The serial-sacrifice experiment was an innovation, which was completely successful. When the clinical data from Japan, Bikini, the laboratory, and Operation Greenhouse are reviewed, few discrepancies can be detected. The clinical and pathological accompaniments of fatal radiation injury are remarkably similar in all large animals. Nothing was learned from the clinical studies at Eniwetok which was not already known. All the experimentation, such as the biochemical studies, bacteriology, and hematology could have been done much more easily and less expensively in the laboratory using X rays.

6.5 CONCLUSIONS

1. The pathological lesions observed in pigs and dogs exposed to an atomic bomb are identical with those caused by equivalent doses of hard X rays.

2. The hematological, bacteriological, and biochemical effects of fatal exposure to atomic bomb gamma rays are the same as those caused by hard X rays.

3. The clinical studies of Operation Greenhouse demonstrated the complete similarity of whole-body radiation injury caused by a single dose of either hard X rays or atomic bomb gamma rays.

4. Excellent colored photographs of the pathology of radiation injury were obtained for teaching purposes.

Chapter 7

Thermal-burn Study

7.1 INTRODUCTION

The flash burn from an atomic bomb explosion is caused by a brief exposure to high-intensity radiant energy. The usual burns encountered in civil and military practice result from contact with lower temperatures and for longer periods of time. It was not known how much influence this difference would have on the local lesion, its systemic effect, the clinical course, and the mortality. Tsuzuki [1] stated that 90 per cent of the Japanese who sought aid in the 1st week after the atomic bombing did so because of burns. At the present time there is not a practical plan for the immediate mass treatment of thousands of burn casualties. The first requisite of rational therapy is to understand the lesion to be treated.

In the previous medical studies of the effects of atomic bombs, no immediate skin biopsies were obtained for comparison with experimental burns produced in the laboratory. The thermal flux and the spectrum have been measured in the course of other weapons tests, but these data were not known to be adequate for biomedical purposes. In the laboratory, skin biopsies of experimental flash burns showed a proportionality between the depth of the injury, the amount of energy applied, and the rate of delivery. The principal objective of the burn study of Operation Greenhouse was to define the characteristics of the flash burn in order that comparable lesions could be produced in the laboratory for detailed study. It was considered to be particularly important to determine the length of time during which burning occurred, since it has been suggested that evasive action may be possible.

The field experiment was designed to provide information on all these points. Serial observations and biopsies of small-area burns were compared with threshold burns resulting from a 1-sec exposure to measured amounts of heat delivered by the focused beam of a carbon-arc searchlight. The relative importance of different portions of the spectrum was investigated by means of filters. The time relation of the burning was studied using shutters actuated by the zero time signal or the flash. The thermal flux was measured by Program 1, and total thermal energy was measured by Programs 1 and 2. Satisfactory burn studies are only possible using anesthetized animals. The conditions of the field experiment were such that it was necessary to employ long-acting anesthetics. The technical methods which were devised for the study are described in detail in the control study,[2] and the field report.[3]

7.2 DISCUSSION OF RESULTS

The design of the burn study has been discussed in Chap. 4, Section 1, and the results are described in detail in another report.[4] It is convenient in this summary to consider the important elements of the experiment separately.

[1] M. Tsuzuki, "Report on the Medical Studies of the Effects of the Atomic Bomb," *General Report, Atomic Bomb Casualty Commission* (Washington: National Research Council, 1947), Appendix 9.

[2] Greenhouse Report, Annex 2.2, Part III.

[3] Greenhouse Report, Annex 2.7.

[4] *Ibid.*

TABLE 7.1 BURNS AS A FUNCTION OF DISTANCE AND ENERGY, UNMODIFIED PORTS

STATION NO.	DISTANCE FROM ZERO (yd)	TOTAL INTEGRATED THERMAL ENERGY CALCULATED[a] (cal/cm²)	ANIMALS OBSERVED	SEVERITY OF BURNS[b]				
				4+	3+	2+	1+	0
Easy Shot								
75	1,325	36–39	6 pigs	6				
			3 dogs	3				
76	2,270	10–13	4 pigs	2	1	1		
			3 dogs	1	2			
77	3,109	5.3–6.9	6 pigs	...	2	3	1	
			3 dogs	1	...	2	...	
78	3,500	3.8–5.2	8 pigs	...	...	...	6	2
			3 dogs	...	1	2	...	.
78a	4,508	2.2–3.1	6 pigs					6
			0 dogs					.
79	5,664	1.1–1.8	8 pigs					8
			2 dogs					2
George Shot								
75	3,460	21–27	9 pigs	...	...	5	3	1
76	4,785	9.5–14	5 pigs	...	...	...	4	1
Heat required for threshold burns in laboratory (cal/cm² in 1 sec)				21–34+[c]	8.5	5.5	3–4.5	3

[a] Calculated from reported yield.
[b] Grading system is described in Annex 2.2, Part IX.
[c] 21 cal/cm² will cause carbonization of skin, which is graded 4+. The degree of carbonization observed at Eniwetok was not seen until heat exceeded 34 cal/cm² in 1 sec, or 30 cal/cm² in 0.33 sec.

7.2.1 Burns as a Function of Distance and Energy

The lesions that occurred behind the unmodified ports were used to study burning as a function of distance and energy. They were also used for the majority of the histological studies. The relation between distance, energy, and burning is shown in Table 7.1. (See Section 1, Table 3.6 and Figs. 4.9, 4.10, and 4.12.) At Station 75 (1,325 yd on Easy Shot), six of eight pigs and all three dogs survived, and all sustained burns with severe carbonization graded as 4+. The burns were invariably more severe in the dark-colored pigs. The initial appearance of the 4+ burns in the white pigs was indistinguishable from lesions of comparable size produced in the laboratory using 34 cal/cm² in 1 sec (the 24-in. focused searchlight), or 30 cal/cm² in 0.33 sec (the 60-in. focused searchlight). At Station 76 (Easy, 2,270 yd) the two black pigs received 4+ burns; of the six white pigs exposed, two received 3+ burns, two had 2+ burns, and two died presumably as a result of the anesthetic. At Station 77 (Easy, 3,109 yd) three of the white pigs had 2+ burns, one had a 1+ burn, and two moved during the exposure and were discarded from the study. Both the black pigs exposed at this distance received 3+ burns. At Station 78 (3,500 yd), only white pigs were exposed, and all six displayed 1+ burns. At the two most distant stations, 4,500 and 5,600 yd from zero, none of the animals were burned. The amount of heat required to produce burns of the severity reported can be estimated from the threshold studies, and the values are in good agreement with the calculated total integrated thermal energy delivered at this distance. The fraction of the total flux delivered during the time that burning occurred is not known because of instrument failures in the physical measurements program. It is evident from Table 7.1, however, that the relation between the calculated value and the biological estimate is surprisingly good. The influence of the color of the skin on the severity of the burn is sum-

[redacted]

TABLE 7.2 EFFECT OF SKIN COLOR ON SEVERITY OF BURNS IN PIGS, EASY SHOT

STATION NO.	SEVERITY OF BURNS IN CHESTER WHITE PIGS					SEVERITY OF BURNS IN DARK-COLORED PIGS				
	4+	3+	2+	1+	0	4+	3+	2+	1+	0
75	4	.	.	.	.	2	.	.	.	.
76	.	2	2	.	.	2	.	.	.	.
77	.	.	3	1	.	.	2	.	.	.
78	.	.	.	6	2	.	.	.	.	.
78a	.	.	.	.	6	.	.	.	.	.
79	.	.	.	.	8	.	.	.	.	.

marized in Table 7.2. The extent of the reflectance of radiant energy by white skin was not measured directly but can be inferred from the comparisons given in this tabulation.

7.2.2 Pathology of the Burns

The lesions produced in the white pigs in the field were identical to those seen in the laboratory from application of high-intensity radiant energy from the focused searchlight or burning magnesium powder. The dry, coagulated surface, without much edema, cyanosis, or weeping of serum was the same. In the severe (4+) burns the character of the central carbonization and the peripheral white ring surrounded by hyperemia was exactly like that observed in the control studies. In all grades of severity from a mild hyperemia to a char the burns inflicted by the atomic bomb duplicated those from the laboratory. The clinical course and healing by sequestration of the eschar were similar. They were unlike low-temperature contact burns, which are variable in depth and edematous in the early stages. Histologically, these burns also resembled those produced with carbon arc or magnesium. They had the same striking demarcation laterally and in depth. The injury penetrated uniformly to a horizontal line where there was an abrupt distinction between living and dead tissues. The healing of burns of all grades of severity in the pig was like that of similar burns created by laboratory sources.

7.2.3 Relation of Spectrum to Burns

There was no burn produced in any animal at any station through the port which transmitted only ultraviolet light. The burns produced behind filters transmitting the visible wave lengths were equal to, or in most cases slightly more severe, than those behind the infrared filters. All the visible light filters were re-examined after the experiment, and it was found that they transmitted some infrared. The prototype filter (Pittsburgh heat-absorbing glass), which was not used in the field had no transmission of infrared beyond 1.0 μ and was selected on this basis. Apparently the filters supplied for the field were produced from a different batch of glass.

7.2.4 Time during Which Burning Occurred

No burn occurred in any animal at any station through the port that was open only for the first 22 msec after Easy Shot, and for the first 30 msec after George Shot. The period of time was considered to include the majority of the first maximum, and the transit of the shutter was considered to occur, for the most part, during the null separating the maxima. The slow-moving shutters which traversed 3 in. in 2 sec had apparently moved only ½ in. before all burning had ceased. It was reasoned that this traverse of one-sixth the distance meant that the burns were sustained during the first ⅓ sec after the detonation. Precise orientation of the shutters was not possible, but the error due to this uncertainty could not have been very great, and it is unlikely that any burning occurred later than ½ sec after the onset of the flash.

7.2.5 Protective Effect of Fabrics

At Easy Shot six animals in the three most distant stations were exposed behind fabrics supplied by the Quartermaster Corps. At the two most distant stations no burns occurred

[redacted]

under any port, and at the other station (77) the fabric gave complete protection. Unprotected skin at this same distance received burns graded as 1+.

7.2.6 Mortality from Anesthesia

At Easy Shot, 4 of 46 pigs and 2 of 15 dogs died during the period of exposure. These deaths are attributed to the anesthetic used: Dial in urea-urethane, administered intraperitoneally. The conditions of the field experiment were such that the anesthesia had to last for at least 14 hr. The dose used was very close to the fatal dose, and the small mortality rate is considered a good result. On George Shot, the weather was inclement, and it was expected that this would increase the mortality in the anesthetized pigs. On recovery, 6 of the 22 animals were dead. The over-all mortality for both experiments was 12 of 84, or 14.3 per cent.

7.3 EVALUATION

To a large extent, the burn study was successful. A number of difficulties occurred which hamper evaluation of the results. The principal ones were the following:

1. The time resolution was not sufficiently accurate. The fast shutters operated at a constant time after the zero signal, and it was not possible to determine exactly when burning commenced in the course of the second maximum. The slow shutters functioned satisfactorily mechanically, but their orientation was somewhat uncertain, with the consequence that the termination of burning could be estimated only approximately. A better device for studying the time resolution has been planned and will be used in future tests.

2. The tropical environment had an adverse effect on the skin of the Chester White pigs. The animals were easily sunburned, and readily developed an eczematoid condition of the skin during rainy periods. This skin condition interfered with proper preparation of the skin for the experiments.

3. The visible light filter transmitted an unexpected amount of infrared.

4. The integrating calorimeters that were placed in the stations in the same relative position as the animals were not entirely satisfactory. The arrangement of the units necessarily resulted in some collimation of the thermal energy, so that the bolometer did not see quite the same amount of radiation as the skin did. The instruments were of the integrating type, and it is not possible to determine the flux during the time when burning occurred.

5. The transmission of the thermal radiation may have been reduced at the quartz windows which protected the skin from sandblasting. An unknown amount of salt spray may have been deposited on the outer surface before the shot. The inner surface may have been affected by condensation of moisture resulting from the confinement of the animals in the closed space. In addition to this, there may have been some attenuation of the thermal radiation close to the ground at the level of the stations during the first ½ sec by dust raised by the earth shock of the blast.

In spite of the foregoing, the burn study yielded significant information of a type which was not available prior to Greenhouse. The studies of the white pigs were more useful than the studies of the dogs, since all the control studies were done with swine. Neither animal has skin which responds to burns in the same manner as human skin. The skin of the young pig, however, resembles human skin in thickness, texture, and general histological appearance. From a practical standpoint, the most useful result was the demonstration of the identical character of atomic bomb flash burns, and flash burns produced in the laboratory with such high-intensity sources as the focused beam of a carbon-arc searchlight and burning magnesium powder. With the data now available, it will be possible to conduct a rational and extensive study of typical burns. Large-area burns may be produced in animals to investigate the complicating effect of radiation injury, the nature of the disturbed physiology, and therapeutic procedures. Small-area burns may be produced with adequate justification in human

volunteers to investigate the changes peculiar to human skin and to test burn dressings.

The importance of reflectance, and the influence of color were adequately demonstrated in the study of the Japanese. The spectral studies at Greenhouse confirm the conclusions derived from the casualty study, and are also compatible with the physical estimate of the thermal radiation. The time dependency of the atomic bomb flash burn is not clearly established by the Greenhouse data, but there is little reason to believe that the period of burning is sufficiently protracted to make evasive action feasible. This conclusion was implicit in the study of the Japanese casualties. Further studies of the time relations will be important principally to aid in the estimate of the critical values for thermal flux required to produce burns of varying severity.

Field studies of burns are difficult to execute because of the complex conditions associated with weapons testing. It is remarkable that the Greenhouse experiment was as successful and profitable as it turned out to be. The effort was considerable, and the expense great, but the positive results are ample justification. When the time resolution and flux measurements are adequately determined, there should be little necessity for further field tests of burns.

7.4 CONCLUSIONS

1. The atomic bomb flash burn can be exactly duplicated with a high-intensity source of radiant energy, such as a carbon arc, magnesium powder, etc.

2. No significant burning occurred during the first maximum of the thermal emission.

3. Burning was completed ⅓ to ½ sec after the detonation of the weapons used at Greenhouse.

4. There was no evidence that ultraviolet radiation contributed to the production of the flash burn.

5. Burns produced through clear quartz windows, heat-resistant glass (low transmission of infrared), and infrared filters were of comparable severity.

6. Dark skin is more severely affected than light skin by a given amount of the thermal radiation of the weapon.

7. Studies of the protective effects of fabrics, etc., can be done with laboratory sources more conveniently and reliably than in the field.

8. Values for integrated total thermal energy as a function of distance calculated from the yield are reliable for estimating the severity of atomic bomb flash burns.

Chapter 8

Radiation Hazard in the Stem of an Atomic Cloud

8.1 INTRODUCTION

The original proposals submitted to the ad hoc committee included several projects to study the exposure of animals to fission products under a variety of circumstances. Since all of the proposals contemplated the use of animals, other than mice, swine, and dogs, they were removed from the approved program in the interest of economy. Among the approved projects was 2.5.4, which involved the use of the mouse thymus-spleen dosimetry system to measure the integrated exposure to gamma radiation during the passage of drone aircraft through the atomic cloud. These mice, and other dosimeters, were to be placed within the fuselage of the aircraft, protected from the inhalation of fission products by appropriate air filters. At the urgent request of the U. S. Air Force, the experiment was redesigned to permit the exposure of three groups of mice, as follows:

1. Exposed only to gamma radiation and used as dosimeters.

2. Exposed to gamma radiation and fission products and used as dosimeters.

3. Exposed to gamma radiation and fission products, and sacrificed immediately after the aircraft had landed. The mice were then frozen and sent to Los Alamos Scientific Laboratory, where the concentration of fission products was determined in lungs, skin, gastrointestinal tract, thyroid, and in the residue of the carcass.

The field study seemed particularly important as an empirical test of the conclusions of various theoretical treatments of the hazard involved in passage through the cloud from a nominal bomb. The significant results of one such treatment (Landahl's) are given in Table 8.1 for comparison with the data from the field test. The summary of Landahl's report was: "The results of the calculations indicate that passing through the radioactive cloud resulting from a nominal atomic bomb would be very hazardous until the cloud reached about 40,000 ft. The chief hazard is that due to hard gamma activity, but under some conditions the inhaled materials might play a significant role." [1] The experimental details and the results of the field study are given in Annex 2.4.[2]

TABLE 8.1 RADIATION HAZARD IN AN AIRCRAFT TRAVELING AT 300 MPH
(Hypothetical)

ALTITUDE (ft)	TIME AFTER DETONATION (sec)	GAMMA-RAY DOSE (r/min)	INHALED RADIOACTIVITY FOR 1ST DAY (mc)
20,000	140	570	4
30,000	300	170	2
40,000	600	75	1

8.2 RESULTS

Dog Shot. Mice placed in each of three B–17 drone aircraft traversed the cloud at 16,000, 18,000, and 20,000 ft. The time of the first passage was 3 to 4 min after the detonation. A second pass was made at the same altitude about 10 to 12 min later. The estimates of dose are integrations of both exposures, but

[1] H. D. Landahl, "Calculation of the Hazard Involved in Passage Through a Radioactive Cloud Resulting from a Nominal Atomic Bomb," *The University of Chicago USAF Radiation Laboratory, Quarterly Report, No. 1* (1951) p 69.

[2] Greenhouse Report, Annex 2.4, Part I, Sec. 3.

it is assumed that the first passage was the more hazardous. The mouse thymus dosimetry system was applied only to the mice that were prevented from inhaling fission products. The results are shown in Table 8.2. The amount of radioactivity in the lungs in every case was less than 1 per cent of the total amount found in the animal. The large values for skin and the gastrointestinal tract are evidence that licking of fur and ingestion of fission products made the mouth the principal portal of entry. It is estimated that 30×10^8 fissions per mouse is equal to approximately 0.1 mc in the mouse. If this amount of radioactivity was evenly distributed and none excreted, the beta- and gamma-ray exposure would amount to approximately 8 rep at infinite time.

Easy Shot. The experimental conditions at Easy Shot were similar to those at Dog Shot, and the results are given in Table 8.2. In each of the three planes, one group of mice for use as biological dosimeters (thymus-weight-change method) was placed in a compartment where the air was not filtered. Thus they were exposed to a mixture of gamma rays from the cloud, beta and gamma rays from fission products in the ventilating air, and internal radiation from ingested and inhaled fission products. The estimates of dose received by these animals are given in Table 8.3. The uncertainty of the biological estimates of dose at this intensity is at least ±20 per cent.

George Shot. The results of this experiment were not satisfactory since the cloud passage was made somewhat later, and the dose was too low for reliable measurement.

TABLE 8.3 EQUIVALENT DOSE OF 230-KVP X RAYS RECEIVED BY MICE ON EASY SHOT

ALTITUDE (ft)	DOSE (r)		NBS FILM-PACK READING[a] (r)
	Gamma Radiation Only	Gamma Radiation Plus Radiation from Fission Products	
16,000	<75	<75	26
18,000	79	137	54
20,000	171	220	135

[a] These films were calibrated for a gamma-ray energy in excess of the average energy of gamma rays from such a mixture of fission products.

8.3 EVALUATION

These experiments were not very precise for reasons which are obvious. The results, however, are of interest since they provide a first approximation of the relative importance of the various sources of radiation for the occupants of aircraft passing through an atomic cloud. The amount of radioactivity found in the lungs, 1 to 3×10^7 fissions per mouse, was very small in comparison with the amount deposited on the fur and available for ingestion. In man, the latter portal of entry would be of no consequence. Even if a man were able to inhale and retain in his lungs and absorb into his body 10^5 times as much radioactivity as the mouse, this amount would not constitute a significant acute or chronic exposure. If this hypothetical amount, 10^{12} fissions, was

TABLE 8.2 DOSE OF GAMMA RADIATION AND QUANTITY OF FISSION PRODUCTS ABSORBED DURING PASSAGE THROUGH THE STEM OF AN ATOMIC BOMB CLOUD

SHOT	ALTITUDE (ft)	RADIOACTIVITY FOUND (10^8 Fissions Per Mouse)[a]				GAMMA-RAY DOSE (r)
		Lungs	Skin	GI Tract	Total[b]	
Dog	16,000	0.1	6	7	15	137
	18,000	0.1	12	10	28	115
	20,000	0.1	29	29	68	165
Easy	16,000	0.07	15	4	21	<75
	18,000	0.1	66	33	106	79
	20,000	0.3	110	51	180	171

[a] 30×10^8 fissions per mouse is equal to 0.1 mc per mouse.
[b] Includes not only the organs listed but also the skeleton and the remains.

strontium^{90}, the total activity after 1 year would be only 0.1 μc, or one-fifth the estimated safe dose as recommended at the 1949 Chalk River Conference. It can be shown that each mouse retained approximately 10^{-16} of the total bomb products. If a man retained 10^5 times this amount, it might include as much as 0.1 μg of unreacted plutonium. This amount is one-fifth of the officially accepted safe dose. It is apparent that even the most pessimistic assumptions with respect to man do not suggest that inhalation of fission products and plutonium during passage through the cloud is an important hazard. The extrapolation from mouse to man under the conditions of these experiments is not particularly defensible, even when the factor is 10^5 instead of the weight ratio of 2×10^3. However, considering only the mice, it can be concluded that the exposure to gamma rays emitted externally to the aircraft was at least 100 times greater than the exposure from fission products inhaled. When the exposure due to the *total* content of fission products is considered, the dose of external gamma radiation was from 3 to 30 times as great as the maximum dose from the ingested and inhaled radioactivity. If an estimate of the hazard to aircrew personnel had to be made from these data, it would be reasonable to use the figures for the lungs alone.

8.4 CONCLUSIONS

1. When an aircraft flies through an atomic cloud 3 to 4 min after the explosion at altitudes varying from 16,000 to 20,000 ft, the principal hazard is the gamma radiation emitted externally to the plane.

2. Making the most pessimistic assumptions from the mouse data, the radiation exposure for man due to inhaled and retained fission products and unreacted plutonium, under the conditions specified, would not exceed the permissible tolerance levels.

3. The experimental results obtained with mice are in good agreement with available theoretical calculations.

[redacted]

Chapter 9

Protection Afforded by a Foxhole

9.1 INTRODUCTION

When the biomedical program was planned in 1949, the ad hoc committee did not approve proposals to conduct studies of primary air-blast injury in the field. This decision was based upon three considerations:

1. There was no evidence that any of the Japanese casualties resulted from air-blast injury.

2. Men and large animals tolerate large amounts of overpressure. At distances from the burst of an atomic bomb where lethal overpressures could occur, the dose of gamma radiation would be of the order of 10,000 r.

3. No control studies were available using a blast wave with the same time-pressure characteristics as that generated by a nuclear explosion.

At that time the lack of interest in field studies of blast seemed reasonable. By the spring of 1951, however, the situation had changed. As a result of new developments in design, attention was directed to the production of weapons for tactical use. The military situation in Korea further stimulated this interest, and the Department of Defense devoted more attention to planning for the tactical use of nuclear weapons. As an aid in such planning, it was necessary to determine the effectiveness of simple, readily constructed shelters (such as foxholes, trenches, dugouts, and bunkers) for the protection of troops in the field. The problem was first examined at Operation Ranger using NBS film packs placed at the bottom of foxholes, the average depth of which was 4 ft. It was shown that the attenuation of gamma radiation from an air burst did not exceed a factor of 10 and in most cases was less. The maximum amount of radiation protection demonstrated did not appear to be sufficient to permit survival at distances where air blast might be a significant hazard.

For these reasons permission was granted to conduct a pilot study using 16 dogs placed in eight foxholes at Item Shot. The foxholes, which were 4 ft deep, 30 in. wide, and 6 ft long, were located at 400, 600, 800, 1,000, 1,250, and 1,500 yd from the zero point (see Section 1, Table 3.7 and Fig. 4.13). The anticipated yield of Item Shot was approximately 50 kt, and at the greatest distance (1,500 yd), the dose of gamma radiation in the open would be approximately 500 r, which is almost twice the LD_{50} (270 r at Easy Shot) for dogs. The preliminary analysis of the Greenhouse data available prior to Item Shot demonstrated that the readings of the NBS film packs could be accepted for an evaluation of the gamma-radiation hazard. Accordingly, it was planned to study the dogs only with respect to the occurrence of blast injury. The typical visible lesion of blast injury is hemorrhage in the lung, and such hemorrhage is often transitory. In order that the maximum effect could be demonstrated, it was planned to sacrifice the animals and perform autopsies about 14 to 16 hr after the blast. This precluded complete evaluation of the extent of the radiation injury as well as any study of the ability of an animal to survive. It was believed that the severity of radiation injury could be judged from the NBS film-pack readings, and that the probable outcome of the blast injury could be predicted from its appearance. The details of the experiment are given in the field report of the project officers, Greenhouse Report, Annex 2.9.

[redacted]

9.2 RESULTS

9.2.1 Biological Effects

Blast damage to three foxholes at 600, 800, and 1,000 yd allowed one dog from each to escape. They were retrieved with no difficulty during the recovery operation. The dog from the 600-yd station was too sick to walk, but the others were lively and appeared normal. The foxhole 400 yd from zero was about one-third full of coral rubble which had buried the animals. The residual radioactivity was too great to permit removal. The remaining 11 dogs were removed from the foxholes without difficulty. All were able to walk and none showed any striking abnormality. The whiskers and the hair of a few animals were slightly singed, but no evidence of serious burning was found. None of the animals had fractures or bruises as a result of the earth shock. Between 7 and 10 hr after the blast the four dogs exposed at 600 yd began to vomit, and in the course of the day some of the others vomited. At the time the animals were sacrificed, 14 to 16 hr after the shot, two dogs from a 600-yd hole, and one from an 800-yd hole, were ataxic, with weakness of the hindquarters and a tendency to fall to one side. Blood counts were made at the time of autopsy, and the severity of radiation injury was estimated tentatively from the total lymphocyte count. On this basis, it was assumed that animals might have survived at 1,000, 1,250, and 1,500 yd. When the dosimeter data were examined (Fig. 9.1), it was evident that the exposure was less than the LD_{50} for dogs (270 r) at some position within the three most distant foxholes. The histological appearance of the lymphatic tissues was compatible with this conclusion.

Gross evidence of primary air-blast injury was seen at autopsy for every distance except the 1,500-yd station. This consisted of hemorrhages in the lungs, emphysema, ruptured eardrums, hemorrhages in the brain, and hemorrhage in the adrenal glands. These findings are summarized in Table 9.1, along with estimates of the peak overpressure at ground level as a function of distance. The brain hemorrhages were obviously disabling, as shown by the development of ataxia, but it is not possible to predict the probable outcome of the animals so affected. It was the opinion of the observers that the pulmonary lesions would not have been fatal if the animals had sustained no other injury. One of the two examples of adrenal hemorrhage would probably have resulted in acute adrenal insufficiency. The dogs that could have survived the radiation injury would not have been handicapped by the effects of primary air blast.

9.2.2 Physical Measurements

NBS film packs were attached to the front wall of the foxholes at 2, 12, 24, 36, and 48 in. below ground level. The results of examination of these dosimeters are shown graphically in Fig. 9.1. The maximum attenuation of gamma radiation at 600, 800, and 1,000 yd was by a factor of 10. At 1,250 yd, it was by a factor of 15, and at 1,500 yd, it was by a factor of 30. A dog lying prone in a foxhole 4 ft deep would receive an LD_{50} at slightly less than 1,000 yd. In the open he would receive the

TABLE 9.1 SUMMARY OF GROSS PATHOLOGICAL FINDINGS IN DOGS IN FOXHOLES AT ITEM SHOT

DISTANCE (yd)	PEAK OVERPRESSURE (psi)	NUMBER OF DOGS	MOST SEVERE GRADE OF INJURY OBSERVED[a]			
			Lung Hemorrhage	Brain Hemorrhage	Ruptured Eardrums	Adrenal Hemorrhage
600	35	4	++	++	+++	+++
800	15	4	+	0	+++	0
1,000	12	2	+	0	+++	0
1,250	9	2	+	0	0	0
1,500	7	2	0	0	0	0

[a] Degrees of damage are indicated as follows: 0=none observed; +=slight; ++= moderate; +++=extensive.

same dose at 1,665 yd. The foxholes at Greenhouse afforded somewhat more protection from gamma radiation than those studied at Ranger. The difference is probably attributable to the fact that Item Shot was detonated on a tower 200 ft high, while the Ranger Shot was an air burst at over 1,000 ft.

Neutron threshold detectors of sulfur and gold were placed at various depths in the foxholes. The gold foils were suspended 18 in. below ground level. There was no attenuation of slow neutrons at this position. The sulfur samples were placed at 18 and 30 in. below ground level. There was no significant difference between samples at the two levels. The sulfur (*i.e.*, >3 Mev) neutron flux inside the foxholes was less than that outside by a factor of 15 at the 600-yd station and a factor of 10 at 1,500 yd.

The pressure recorders placed on the foxholes were damaged by the blast and failed to give usable data. The temperature recorders also were damaged, and no significance can be attached to the records from them.

9.3 EVALUATION

This experiment was assembled late in the course of Operation Greenhouse, and it was not possible to perform control studies of any sort. There were only 16 adult dogs left in the large-animal colony and this limited the scope of the problem considerably. The results of Easy Shot were most helpful in evaluating the hazard from gamma radiation at various positions within the foxholes. It is proper to consider that the NBS film-pack readings were reliable measurements of dose, and it is reasonable to assume that sublethal radiation injury occurred at the bottom of Station 86f (1,000 yd) and in Stations 86g and 86h at any depth greater than 12 in. below the ground line. The data are fairly consistent and demonstrate that some individuals in foxholes 4 ft deep at 600 yd from a 50-kt shot would be affected for some time after such an experience. Because of the small number of animals used, it is not possible to make a more precise statement at this time.

The evidence is fairly clear that primary air-blast injury inflicted by peak overpressures of 35 psi or less is not disabling for dogs. It would be unusual if the same amount of overpressure should be more destructive to men than to dogs. Fatal radiation injury of animals at the bottom of a foxhole 4 ft deep would be unlikely at distances of greater than 1,000 yd under the specific conditions of this test.

9.4 SUMMARY

1. Foxholes 4 ft deep protected dogs from fatal primary and secondary blast injury, and from fatal thermal burns at 600, 800, 1,000, 1,250, and 1,500 yd from a 50-kt weapon fired on a 200-ft tower.
2. Primary air-blast injury occurred in animals in every foxhole placed at 1,250 yd and closer to zero. Except in the nearest foxholes, the air-blast injury was minimal.
3. At the bottom of the foxholes the attenuation of the gamma radiation varied from a factor of 10 to a factor of 30, depending on distance from zero.
4. The dogs at 1,000, 1,250, and 1,500 yd received sublethal doses of radiation. For a weapon of the same yield, the LD_{50} in the open was 270 r delivered at 1,665 yd.
5. A foxhole affords protection by a factor of 10 to 15 against sulfur neutrons (energies of 3 Mev or greater).

Chapter 10

Discussion

10.1 ADEQUACY OF THE EXPERIMENTATION

The biomedical program was a complicated affair in comparison with the ordinary laboratory experiment. The difficulties that were encountered were to a large extent inherent in the conditions of the weapons test and could not have been avoided. These difficulties included the geographical location, the uncertainty of the yield, the inability to observe the animals immediately before and after exposure, the impossibility of exact repetition of experimental conditions, and the necessity for using a large number of subjects. In spite of the opportunities for trouble, only a few of the experiments were failures. It is instructive to examine these cases with reference to the reasons:

1. The mouse thymus system of dosimetry of neutrons failed at Easy Shot, when all the mice in seven of the eight stations died of acute radiation injury before the 5th day. The stations had been located on the basis of the best data available, but the new type of weapon used for Easy Shot emitted more neutrons than was expected.

2. The mouse thymus system of gamma-ray dosimetry failed at George Shot to the extent that all mice in six of the eight stations were dead before the 5th day. The yield of this weapon proved to be much greater than the maximum predicted, so that this failure to obtain biological data was unavoidable.

3. The RBE of neutrons was not determined in any of the experiments using either mice or *Tradescantia*. In the case of mice, good values for apparent dose in roentgens equivalent man were obtained at Dog and George Shots. In the case of *Tradescantia*, effects due to neutrons were observed, but it is not proper to assign any numerical significance to them. It was known before the experiment that the yield of chromosomal aberrations is quite dependent upon the energy of the neutrons used. No calibrations were available for neutrons of energy comparable to those inside the lead hemispheres. Moreover, there were no reliable physical detectors in the same geometry which would permit an evaluation of the exposure. In retrospect, it appears to the author that the *Tradescantia* neutron experiment was an attempt to do the impossible.

4. Gamma-ray dosimetry with *Tradescantia* was accomplished at a few points, but not in sufficient detail for any useful purpose. Estimates of biological dose were made using *Tradescantia* which were in fair agreement with the values obtained by physical methods. The uncertainty of each *Tradescantia* estimate was larger than that for the mouse thymus system. The failure of the *Tradescantia* system to provide adequate data was due to loss of plants by accidents, and also to the decision of the project officer to devote the greater effort to the measurement of neutrons. The program director concurred in this decision. The few data available suggest that the RBE of the gamma radiation was unity as compared to 230-KVP X rays, but the evidence is not so conclusive as in the case of the studies using mice.

5. Depth-dose measurements in swine and mouse phantoms were not successful. The films used were energy-dependent to such an extent that the density readings cannot be interpreted at the present time. The film can be calibrated using a source with the effective energy determined for the gamma radiation;

but this would not help matters. One of the reasons for the depth-dose study in unit-density material was to explore the question of the apparent collimation of the gamma radiation. Some evidence for this was obtained in the IBM analysis of mouse mortality. The results, as a whole, however, failed to yield the information that was desired.

6. In the thermal-burn study, the time dependency of the burning portion of the thermal flux was not defined as accurately as was desired. This failure was due to inadequacies of the equipment, which can be corrected for later tests. The radiation calorimeters that were exposed in the same general geometry as the animals were not satisfactory. The data obtained from bolometers with a long time constant were of no assistance in the estimation of either the thermal flux, or the total thermal energy delivered during the ½ sec (approximately) when burning occurred. The heat-absorbing glass filters transmitted more infrared than was expected on the basis of control tests. Because of this, it is not possible to assess accurately the relative importance of visible light and infrared in the production of clinical burns.

Of the 18 projects which were included in the protocol of the program, none was a complete failure. The data obtained using *Tradescantia, Glomerella,* corn seed, the swine phantoms, and the mouse phantoms, were either not usable, or at best were in agreement with other, more reliable, measurements. The principal conclusions that can be drawn from the operation not only do not depend on the foregoing data, but also were not compromised by the partial failure of these experiments.

From the experiments which were not failures, results were obtained which can properly be called adequate. The biological estimates of gamma-ray dose as a function of distance employed large numbers of animals. The numbers used at any location were determined in consultation with biometricians. It was agreed in advance that sufficient numbers of animals should be used so that the results would be significant at the 95 per cent level of confidence or better. When the correlated errors of estimate associated with any location are summated, it appears that the individual estimates of dose did not exceed 15 per cent. Such a result is somewhat better than the predicted error for estimates of dose using the NBS film pack. It is proper to assume that the biological estimates of effective neutron dose were equally reliable. The physical neutron detectors yielded measurements which were quantitatively incomplete. However, since the RBE of neutrons is not known, it is not possible to assess the reliability of the results of the mouse study.

10.2 SIGNIFICANCE OF THE DATA

The dose-mortality response of the mice provides interesting information on the reliability of the data and the adequacy of the experimental design. The standard deviation of the LD_{50} as determined by probit analysis is very small, *e.g.,* 2.2 r for an LD_{50} of 759 r. This coefficient of variation, therefore, was 0.3 per cent, and this means that the variance of the reactions of the groups of mice in the stations of the 70, 71 series was quite small. When used in this manner, the concept of variance includes the behavior not only of the animals, but also of the radiation. It is correct to conclude that the animals and the radiation displayed a high degree of homogeneity. The small coefficient of variation is particularly significant in view of the results of the IBM analysis. This study disclosed a pronounced effect of location within the exposure unit on the dose-mortality response and on the LD_{50}. The experimental design was such, however, that these variables were controlled, and did not introduce either bias or uncertainty into the results.

The large-animal dose-mortality studies were designed in such a fashion that the 95 per cent confidence interval of the LD_{50}, expressed as distance, should not exceed 100 yd. It is gratifying to note that in the case of the swine the interval was 60 yd, and in the case of the dogs it was 100 yd. The confidence interval of 100 yd was chosen since this is the approximate length of the ordinary city block. It seemed realistic to assume for civil defense purposes, that it is not necessary to know the

MLD distance with greater precision than this. The coefficient of variation for the large animal dose-mortality response was about 5 per cent, which is evidence of a satisfactory experiment.

The mouse and dog studies are considered to be very significant, since they provide good information on the biological effectiveness of the gamma radiation of a nuclear weapon. Regardless of how RBE is calculated, its value is close to unity. The evidence appears to be overwhelming that the energy and the intensity of the nuclear radiation do not have any significant influence on the response of these animals. The discrepancy in the case of the swine may be related to the high effective energy of the gamma rays, or to the difference in age and size of the animals used for the field and control tests.

The depth-dose study that was successful (the spherical phantoms) failed to supply a number for the HVL of the gamma radiation in unit-density material. However, a curve was obtained that was sufficiently characteristic to permit comparison with other types of radiation. In the spheres with the thickest walls (17.5 cm) the air dose of the weapon radiation was reduced to 67 per cent. Using this curve as the basis for comparison, it was found that the unfiltered beam of the 10-Mev betatron possessed the same effective energy as the weapon radiation. The studies using lucite spherical phantoms also showed that the weapon radiation did not vary in quality throughout the range of biomedical interest, regardless of the yield of the weapon. Although only two sets of spherical phantoms survived Easy and George Shots, respectively, the readings of the three Sievert chambers in each of the seven spheres at each station were entirely consistent. The variation of the readings of the chambers was less than 5 per cent.

The appearance and the course of the flash burns was unequivocal evidence of the similarity among lesions produced by the weapon, and those produced by such high-intensity sources as the carbon arc and burning magnesium. The estimates of the amount of energy required to produce such burns in a comparable period of time are semiquantitative at best. Nevertheless, the values inferred are reasonable and are in good agreement with the best physical measurements.

The results obtained in drone aircraft and in the foxhole experiment should be considered as first approximations. The nature of the experiments was such that reliable quantitative data were neither expected nor obtained. However, the consistency of the results, and the good agreement with theory, in each case, indicate that they may be considered as significant. Future studies of these problems should be conducted with particular attention to the design of the experiment, so that significant quantitative data can be collected. It is proper to conclude that both were successful pilot studies.

The clinical studies confirmed again that the syndrome of whole-body radiation injury is the same in all its essential details in large mammals and in man. It is apparent that the intensity of the gamma radiation has no effect on either the clinical manifestations or the outcome of the syndrome. This is not a particularly novel conclusion, but it gains significance under current conditions. The essential identity of whole-body radiation injury, of whatever cause, simply means that it is not necessary to explode atomic bombs to provide radiation for experiments in pathogenesis or therapy. The results obtained in the laboratory using gamma rays or X rays and appropriate animals can be transferred confidently to human applications.

10.3 APPLICATION OF THE DATA

The gamma-ray experiments provide abundant justification for the continuation of animal studies in the laboratory using appropriate sources of hard or supervoltage X rays, or gamma rays, such as those of cobalt^{60}. In the range of intensity from about 5 to 2,000 r/min, there does not appear to be any marked difference in the biological effect per roentgen of single, whole-body doses. This conclusion, if it is true, liberates the experimenter from strict adherence to a limited number of

sources, and allows him much more freedom in planning his research.

The clinical studies reaffirm the condition of analogy that exists in the syndrome of whole-body radiation injury caused by single doses of X rays, hard gamma rays, and the gamma radiation of a nuclear weapon. It should not be necessary to use a nuclear weapon as a source for experimental clinical studies. A weapon may be a useful source when it is desired to perform critical pharmacological studies. In such a circumstance, the low variance of the data, the large numbers that can be exposed simultaneously, and the geometrical gradation of dose are desirable features, which cannot be attained otherwise.

The neutron experiments were of particular importance with respect to many practical problems. It was noted that the lead shields reduced the sulfur neutron flux by a factor of 5; but the theoretical examination of the problem demonstrated that this resulted from moderation to lower energies for which no good threshold detector is available. The mice effectively integrated the neutron dose, and permitted a reliable evaluation of the exposure behind the shield. The theoretical examination also disclosed that approximately 90 per cent of the biological effect must have been caused by fast neutrons. It can be concluded from this series of circumstances that evaluation of shielding or shelters must be performed using integrating neutron dosimeters with qualities analogous to a biological subject, such as the mouse. The inability to further interpret the Greenhouse neutron data is due to a lack of fundamental knowledge regarding many aspects of neutrons. It is probable that the questions posed by the 1951 Eniwetok tests will stimulate further research on neutron dosimetry.

The determination of good values for the MLD of dogs and swine is of biological interest since it permits comparison with other types of intensities of radiation. The information, however, does not alter the uncertainty that exists regarding the MLD for man. The geometry of the explosion of a nuclear weapon introduces a great many variables which complicate any attempt to develop a simple method for estimating expected dose as a function of distance. In retrospect, it may have been naive to anticipate that the value for LD_{50}, expressed as distance, obtained from a tower shot could be applied to an air burst, a surface burst, or a burst over an urban region. The most important result of the dose-mortality study of large animals was the determination of good values for the LD_{50} expressed in roentgens measured in air. If it is granted that the MLD for man approximates that for swine of comparable size, it is possible to develop personnel dosimeters on a sounder basis than was the case before the tests. In fact, the combination of the large animal data, and the specification of quality of the beam should be a great help to those responsible for the development of personnel dosimeters.

The burn studies had two significant results. First, the time of burning was clearly shown to be no longer than the first ⅓ to ½ sec after the detonation. It is apparent that this is too short a time for any successful evasive action to be contemplated or executed. Second, the flash burn of a nuclear weapon can be reproduced exactly by a high-intensity thermal source acting for ⅓ to ½ sec. Such being the case, detailed studies of every phase of the burn problem can be conducted in the laboratory. Burn dressings, the physiological disturbances that follow large-area burns, and the complicating effect of radiation injury can all be studied conveniently and with precision in permanent laboratories, and without the difficult operational problems that are inevitable in field experiments.

The best use that can be made of the experiments in drone aircraft and in foxholes is as a starting point for more detailed and better controlled studies at some future weapons test. It is apparent from the results that further experimentation is necessary, and the pilot studies also served to raise several questions which had not been considered seriously before.

10.4 CONCLUSIONS

It is the opinion of the author that the biomedical program was successful. The proportion of good results exceeded expectations. From a broad point of view, the best result was the demonstration that many critical medical problems can be investigated reliably and more effectively in the laboratory than in the field. Because of the expense, complexity, and uncertainty of field tests, this is a most important conclusion.

Chapter 11

Summary

1. It was possible to use mice and *Tradescantia* as biological dosimeters successfully to measure gamma radiation as a function of distance. Of the dosimetry systems used, the mouse thymus system was the most satisfactory.

2. Using mice, it was found that the biological effectiveness of gamma rays from a nuclear weapon was comparable to that of X rays generated at 200 to 2,000 KVP. The RBE of such gamma rays is approximately unity with respect to X rays.

3. It was possible to use mice as biological dosimeters to measure the biological effect of neutrons behind lead shields as a function of distance from the bomb. The effect was measured in terms of equivalent roentgens of 230–KVP X rays. These data were used to estimate the biological effect outside the shielding. It was not possible to determine the RBE for specific spectral components of the neutron flux because of the inadequacy of both physical spectral measurements and laboratory biological data.

4. The MLD for swine, whose average weight was 70 lb, was found to be 230 r. The MLD for dogs, whose average weight was 25 lb, was found to be 270 r.

5. The biological effectiveness for dogs of gamma rays from a nuclear weapon was approximately 15 per cent greater than that of supervoltage X rays. In the case of swine, the gamma rays were approximately 80 per cent more effective than supervoltage X rays.

6. The clinical course, complications, and pathological lesions of whole-body radiation injury in dogs and swine caused by a single dose of gamma rays of an atomic bomb is indistinguishable from the syndrome in human subjects. It is also indistinguishable from the syndrome of whole-body radiation injury caused by exposure to X rays generated at 250 to 2,000 KVP.

7. The effective energy of the gamma radiation of a nuclear weapon at distances of biomedical interest is comparable to that of the unfiltered beam of X rays produced by a 10–Mev General Electric betatron.

8. Clinical flash burns are inflicted during the time interval 25 to approximately 300 msec after detonation. The lesions are indistinguishable from the flash burns inflicted by a focused carbon arc, or burning magnesium powder, when the period of burning is approximately 0.3 to 1.0 sec. This being the case, evasive action is not possible.

9. At distances where 3rd degree burns were inflicted, there was no evidence that there was sufficient ultraviolet to cause skin injury.

10. The burns inflicted through polished, clear quartz, infrared broad-band filters, and Pittsburgh heat-absorbing glass were qualitatively the same. Dark-skinned animals received more severe burns at a given distance than did white-skinned animals.

11. In aircraft that traversed the stem of an atomic cloud 3 to 4 min after detonation at altitudes of 16,000 to 20,000 ft, the dose of gamma radiation from sources external to the plane exceeded the maximum possible dose due to inhalation of fission products. The ratio of the exposure from these two sources appeared to vary from 30 to 100.

12. Animals placed in foxholes at distances from the tower where gamma radiation was not lethal did not display any evidence of serious blast injury.

13. Biological and medical experiments in the field in connection with tests of atomic

weapons can be conducted satisfactorily. The usefulness of such tests is strictly limited by the allied conditions and by the uncertainties of experimental weapons.

14. Many of the most important problems associated with the medical care of atomic bomb casualties can be studied much more effectively in the laboratory using appropriate sources of nuclear and thermal radiation.

Appendix A

Statistical Analysis of the Mouse Mortality Data

A.1 INTRODUCTION

The mouse dose-mortality study consisted of two parts: (1) the determination of mortality rate as a function of distance (Project 2.4.1.1), and (2) duration-of-life study of the mice surviving exposure to gamma radiation (Project 2.5.1.1). The results of the first part have been described in Sec. 3.3, where the data were used principally to examine the RBE of the nuclear gamma rays. The clinical observations on the survivors are reported in Appendix B. The mice, in groups of 60 or 220, were placed in wooden trays divided into individual cells. Each cylindrical exposure unit of the 70, 71 series accommodated six trays, the cells of which contained either mice, or mouse phantoms made of masonite. Each mouse was identified individually, and his position within the cylindrical unit was recorded. For each animal a code sheet was prepared which contained the following data: age, sex, weight, station location, position within the station, date of death, and apparent cause of death. These data were transcribed on IBM cards, and the mortality data were submitted to an extensive analysis.

The statistical studies of the crude mortality data were performed by E. P. Cronkite, project officer for Project 2.4.1.1. In his analysis all the animals at a given location were treated as a group, the members of which it was assumed had received the same dose of gamma rays. The data yielded the dose-mortality curves shown in Figs. 3.7 and 3.8. In addition to this, attention was directed to survival time within the 28-day limit of the field experiment. The group of mice at any one station was comparable to that at any other station, but the possibility existed that individual mice in a given station might receive different doses of radiation or might differ in their radiosensitivity. This possibility was investigated by Jack Moshman of the Oak Ridge National Laboratory using the IBM cards prepared for each mouse. The preliminary results of his statistical analysis are presented in this Appendix.[1]

A.2 SUMMARY OF THE MORTALITY DATA

The over-all mortality data were examined to test the hypothesis that age, sex, weight, and location in the exposure unit had no influence on the response to the range of doses of gamma radiation. This examination is of particular importance with respect to the influence of position. It was hoped that the film packets in the mouse phantoms could be used to evaluate the variation in dose that occurred throughout the assembly of trays in the exposure unit. These films were energy-dependent, however, and the results obtained from a study of them were unsatisfactory. Such being the case, the best measure of the modifying influence of position in the tray assembly is the dose-mortality response of the animals. Reductions in mortality rate as a function of position can be interpreted to mean that the dose delivered to such a position was reduced in some manner.

[1] This statistical summary was prepared by Jack Moshman, Oak Ridge National Laboratory.

A.2.1 Sex

Of a total of 2,361 males, 47.5 per cent were killed.[2] This corresponds to 48.3 per cent mortality among 2,358 females. The difference is clearly not significant.

A.2.2 Age

AGE (weeks)	NUMBER EXPOSED	PER CENT MORTALITY
7	31	61.3
8	166	48.8
9	1,263	48.9
10	647	47.3
11	578	46.7
12	2,032	47.7

A chi-square analysis of the above data yields $\chi^2=3.685$ with 5 deg of freedom, a value which will occur by chance over 50 per cent of the time. On the basis of this test, there is no significant difference between gross mortality among age groups.

A.2.3 Weight

WEIGHT (g)	NUMBER EXPOSED	PER CENT MORTALITY
10 to 14	2	50.0
15 to 19	817	45.0
20 to 24	2,162	47.9
25 to 29	1,569	48.8
30 to 34	166	55.4

Excluding the first group, the ascending nature of the per cent dead indicates that there may possibly be a greater susceptibility with increasing weight, but four proportions are too few to establish significance. A value of $\chi^2=7.206$ was obtained from these data. With 4 deg of freedom, such a value would be exceeded by chance between 10 and 20 per cent of the time in repeated samplings if all the mortality percentages were, in fact, equal. Hence, we cannot ascribe a significant difference to these data.

[2] Throughout this report, the per cent killed refers only to those animals dead before the 29th day after Easy Shot.

A.2.4 Trays

The trays of mice in each exposure unit were numbered from the bottom (1) to the top (6).

TRAY	NUMBER EXPOSED	PER CENT MORTALITY
1	747	36.4
2	845	42.5
3	829	62.0
4	793	58.3
5	784	43.5
6	721	43.8

Analyzing all six trays together gives $\chi^2=159.959$, which with 5 deg of freedom is significant far beyond the 1 per cent level. The higher mortality evident for trays 3 and 4 is due to the fact that the mice in Stations 70a to 70i were placed solely in these trays. Their proximity to the blast resulted in 100 per cent mortality which gave these trays an unrepresentative high figure. If these two trays are eliminated from the analysis, then $\chi^2=10.962$, which with 3 deg of freedom would be exceeded by chance between 1 and 2 per cent of the time. Hence, even trays 1, 2, 5, and 6 are not homogeneous. It is obvious that tray 1 is significantly less than the other trays. The immediate physical explanation is the position of tray 1 on the bottom. Apparently there was an attenuation of the gamma radiation by the contents of the exposure unit, resulting in a lower mortality.

A.2.5 Position in Tray

In Table A.1 are summarized the proportion of mice killed in each of the 45 positions in the standard tray for all trays at all stations. Row 1 was the one facing away from the bomb, row 3 was the closest. The proportion of mice killed in the front row was greatest and that in the back row was least, a result that is not wholly unexpected. However, it should be noted that in Columns 1, 2, 8, and 14, the percentage of mortalities in row 2 exceeded those in row 3.

Columns 1, 2, 14, and 15 were not used for mice at Stations 70a through 70i. Column 8 was similarly biased, and furthermore had

[redacted]

TABLE A.1 PROPORTION OF MICE DEAD BY POSITION IN TRAY

ROW	COLUMN	1	2	3	4	5	6	7	8
1	Proportion	0.2162	0.2857	0.4048	0.4365	0.4524	0.4318	0.4167	0.3125
	Number exposed	37	56	126	126	126	132	132	64
2	Proportion	0.3789	0.5192	0.5159	0.4841	0.5079	0.5152	0.5076	0.4643
	Number exposed	95	52	126	126	126	132	132	28
3	Proportion	0.3571	0.4286	0.5714	0.5840	0.6111	0.5530	0.5489	0.3750
	Number exposed	56	56	126	125	126	132	133	64
TOTALS									
Proportion		0.3404	0.4085	0.4974	0.5013	0.5238	0.5000	0.4912	0.3654
Number exposed		188	164	378	377	378	396	397	156

ROW	COLUMN	9	10	11	12	13	14	15	TOTALS
1	Proportion	0.4015	0.4318	0.4603	0.4400	0.4113	0.3036	0.3036	0.4045
	Number exposed	132	132	126	125	124	56	56	1550
2	Proportion	0.4849	0.5079	0.5280	0.5159	0.5081	0.5385	0.3895	0.4934
	Number exposed	132	126	125	126	124	52	95	1597
3	Proportion	0.5455	0.5952	0.5635	0.5952	0.5680	0.3929	0.4286	0.5401
	Number exposed	132	126	126	126	125	56	63	1572
TOTALS									
Proportion		0.4773	0.5104	0.5172	0.5172	0.5228	0.4085	0.3785	0.4798
Number exposed		396	384	377	377	373	164	214	4719

many phantoms replacing exposed animals. If these five columns are eliminated, and Columns 3 to 7 and 9 to 13 are examined for homogeneity, we find that there is less than one chance in a hundred that such an hypothesis would be justified. It is somewhat difficult to assign the source of this heterogeneity to any other factor than the depth-dose effect. It appears as though greatest susceptibility occurs in Columns 5 and 13.

A.3 SUMMARY OF THE PROBIT RESPONSE

The dose-mortality response determined by a probit analysis yields two additional parameters that can be used to examine further the hypothesis that age, sex, weight, and location in the exposure equipment had no influence on the response to gamma radiation. The values for dose that were used in the probit analysis were the same as the values used in Sec. 3.3. These were the average readings of the Sievert ionization chambers placed in the lucite spherical phantoms with wall thicknesses less than 5.0 cm. This dose should be considered as a measurement in air. The slope of the curve of dose as a function of distance was based on the value for mean free path of the gamma photons estimated biologically, and was taken as 360 yd. One parameter, the LD_{50}, determined for the various age, sex, weight, and location groups can be considered as a measure of the effective dose received by the group. Thus, if the LD_{50} for a given tray location was larger than the average, or over-all LD_{50}, this would indicate that the location was shielded, or resulted in an attenuation of the exposure. In effect, the higher value for LD_{50} indicates that the animals so placed behaved as if they were closer to the source and thus exposed to a higher dose of radiation measured in air, some fraction of which had been attenuated by the features of the exposure equipment. The second parameter, the slope of the probit regression line, is a measure of the biological effectiveness per roentgen of the radiation de-

[redacted]

livered to a specific location or to a specified group of mice. Ideally, the slopes of the regression lines for all groups should be homogeneous. The significance of variations of slope in radiation dose-mortality studies is not known with certainty. In pharmacology, slope is related to potency, and there is some reason to believe that in the case of radiation, slope is related to the quality of the beam.

A.3.1 Sex

The pattern of response of the two sexes was quite similar. One can differentiate neither between slopes nor LD_{50}'s statistically (see Table A.2).

A.3.2 Age

The standard errors of the various age groups differed significantly among themselves, making it difficult to compare the respective LD_{50}'s. On the 5 per cent level of significance there does appear to be a significant difference among ages. The pattern followed is that of increasing dose necessary to kill 50 per cent of the mice of increasing ages. The difference between any two adjacent groups is not significant, but it is for any two nonadjacent age groups. Presumably, within the limits studied, greater age involves greater resistance. The slopes also differed (probably 1 per cent) among themselves suggesting a nonparallel response among age groups.

A.3.3 Weight

Although there is a significant correlation, as would be expected, between age and weight, the LD_{50}'s did *not* vary significantly among weight groups. There exists considerable overlapping of 95 per cent confidence intervals of all classes. The slopes also did not show a significant difference although there did appear a rough parallelism between them and the slopes for corresponding age groups.

TABLE A.2 SUMMARY OF PROBIT RESPONSE DATA

GROUP	SUBGROUP	EQUATION[a]	$\sigma_b \times 10^{-3}$[b]	LD_{50}	$\sigma_{LD_{50}}$[c]
Sex	Male	$y=-7.0914+0.01596x$	0.767	757.61	3.01
	Female	$y=-6.9708+0.01590x$	0.640	752.88	3.03
Age (weeks)	7–9	$y=-8.136+0.01777x$	1.174	739.22	3.79
	10	$y=-5.056+0.01341x$	1.274	749.88	6.51
	11	$y=-4.421+0.01250x$	1.198	753.46	6.98
	12	$y=-7.298+0.01615x$	0.870	761.39	3.25
Weight (g)	15–19	$y=-8.389+0.01773x$	1.602	755.16	5.10
	20–24	$y=-7.083+0.01602x$	0.774	754.21	3.05
	25–29	$y=-6.365+0.01495x$	0.877	760.20	3.79
	30–34	$y=-9.197+0.01895x$	2.385	749.18	9.60
Tray	1	$y=-8.708+0.01764x$	1.431	777.09	4.72
	2	$y=-6.696+0.01523x$	1.190	767.96	5.01
	3	$y=-4.706+0.01295x$	1.337	749.50	6.78
	4	$y=-6.107+0.01488x$	1.392	746.44	6.00
	5	$y=-8.668+0.01828x$	1.565	747.70	4.69
	6	$y=-8.492+0.01823x$	1.744	740.10	4.85
Rows in Tray	1	$y=-8.943+0.01757x$	1.003	793.57	3.58
	2	$y=-9.600+0.01925x$	1.182	758.43	3.18
	3	$y=-7.138+0.01696x$	1.184	715.68	3.91
All animals		$y=$		759.	2.2

[a] y is probit response to dose x.
[b] σ_b is standard error of the slope.
[c] $\sigma_{LD_{50}}$ is standard error of the LD_{50}.

[redacted]

A.3.4 Trays

As evidenced previously in the crude mortality proportions, there was a difference among the trays. The computed LD_{50}'s for trays 1 and 2 were 777 and 768 r, respectively, while all the other higher trays varied between 740 and 750 r. The difference between the first two trays was not statistically significant, but their relative magnitudes were in the order expected. The variations of the LD_{50} between trays are entirely compatible with the variations of the mortality rate. The lowest tray (tray 1) was protected by the other trays; it had the lowest mortality rate; and the highest LD_{50}.

The slopes of the individual probit regression lines for the trays were also examined for homogeneity. With less than a 50 per cent probability of error, it appears that the slopes are not homogeneous. The middle trays show a significantly smaller slope than the outer trays. It is difficult to explain a smaller potency per roentgen for the center trays.

A.3.5 Rows

Here again, as in the crude mortality study, there is a significant difference among rows, presumably a result of the geometrical arrangement. Row 3, facing the blast had an LD_{50} of 716 r, and the row farthest away had a corresponding figure of 794 r. The explanation is the same as that used in describing the effects in the trays.

Among the three rows in the experimental setup the slopes did not differ significantly, as shown by the range 0.0023, while among the trays the range of variation was 0.0053, which was a significant variation. There is no explanation for this discrepancy.

A.4 AGE-WEIGHT STUDY

It was remarked above (Secs. A.3.2 and A.3.3) that there appeared to be a significant relationship of LD_{50} to age for all mice combined, but not so for weight. In order to examine this phenomenon in somewhat greater detail, individual probit regression lines were fitted to each age group within each weight class. A summary appears in Table A.3. Weight classes, 30 g and over, are omitted because of the scanty data.

It is evident that except for the 25 to 29 g mice there is little indication of variation of LD_{50} with age, nor is there any recognizable pattern among the slopes.

After the 8-week-old mice were eliminated because of the large standard errors associated

TABLE A.3 AGE–WEIGHT PROBIT RESPONSE DATA[a]

WEIGHT (g)	AGE (weeks)	EQUATION	$\sigma_b \times 10^{-3}$	LD_{50}	$\sigma_{LD_{50}}$
15–19	8	$y = -10.314 + 0.02042x$	7.683	749.95	16.92
	9	$y = -9.212 + 0.01880x$	2.933	755.96	8.19
	10	$y = -8.286 + 0.01723x$	4.598	771.11	13.69
	11	$y = -13.436 + 0.02415x$	7.329	763.40	12.18
	12	$y = -7.102 + 0.01612x$	2.663	750.74	10.35
20–24	8	$y = -9.637 + 0.02004x$	6.190	730.39	14.64
	9	$y = -9.467 + 0.01914x$	1.942	755.85	5.15
	10	$y = -5.500 + 0.01413x$	1.912	743.10	9.14
	11	$y = -5.875 + 0.01442x$	2.048	754.16	9.21
	12	$y = -7.313 + 0.01624x$	1.309	757.72	4.84
25–29	8	$y = -5.684 + 0.01410x$	4.961	757.73	25.57
	9	$y = -7.222 + 0.01643x$	2.231	743.88	7.86
	10	$y = -4.190 + 0.01221x$	1.920	752.66	11.42
	11	$y = -4.958 + 0.01316x$	2.382	756.69	12.36
	12	$y = -7.656 + 0.01641x$	1.373	771.24	5.09

[a] The symbols used have the same meaning as in Table A.2.

[redacted]

with their parameter estimates, the remaining slopes and LD_{50}'s were subjected separately to an analysis of variance to gain a better insight into the possible age and weight differentials. No significance was noted for either age or weight in each of the two analyses (slope and LD_{50}'s). It was not possible in this manner to examine the interaction of age and weight on the slopes and LD_{50}'s. In fact, the interaction was assumed to be zero. It is planned, by considering the right-hand columns in each tray to be a replication of the left-hand columns, to set up what is equivalent to a replicated experimental design. This will enable a test of the zero interaction hypothesis to be made. It is quite possible that radically different results may be obtained.

A.5 CONCLUSIONS

1. The combined mortality rate for 4,719 mice exposed to gamma radiation from Easy Shot was 47.9 per cent. There was no sex difference in susceptibility.

2. When the influence of age on susceptibility was examined, the gross mortality data indicated no influence, but the estimates of the LD_{50} revealed that within the limits studied greater age results in greater resistance.

3. When the influence of weight was examined, the gross mortality data indicated a greater susceptibility with increasing weight, but the estimates of the LD_{50} showed that they did not vary significantly among the weight groups.

4. The mice in the bottom trays of the exposure stations were shielded by the material between them and the bomb to such an extent that the mortality rate was 36 per cent, as compared with 44 per cent in the top tray. The LD_{50} for the bottom trays was 777 r, and for the top trays 740 r, which represents a significant reduction in the amount of radiation to which they were exposed.

5. The mice in the front row of cells that were closest to the bomb had a mortality rate of 54 per cent, while those in the rear rows had a rate of 40 per cent. The protective effect of the material in the exposure unit is also shown in the LD_{50}'s. The LD_{50} for the front rows was 716 r, and that for the rear rows was 793 r.

6. The materials of which the trays were constructed, the mice, and the phantoms resulted in a significant attenuation of the gamma rays emitted by the bomb.

[redacted]

Appendix B

Study of Surviving Mice, Interim Report (Projects 2.5.1.1 and 2.5.1.2)

B.1 INTRODUCTION

It was expected that approximately one-half the mice exposed to Easy Shot for the study of mortality rate as a function of distance would survive the 28-day period of observation. According to the plans, these mice were shipped by air to the Oak Ridge National Laboratory. They are to be retained for the duration of life and are being studied with respect to the effect of gamma radiation on longevity, on the incidence of neoplasms, and on the occurrence of cataracts. Of the 4,560 mice exposed to Easy Shot by Project 2.4.1.1 in the single cylinder units, 2,208 survivors were shipped to Oak Ridge. In addition to these animals, 470 mice were placed in lead-domed hemispherical units at Easy and George Shots for exposure to neutrons. Of the 300 mice exposed to Easy Shot, 145 survived; and of the 170 mice exposed to George Shot, 139 survived. All but five of the survivors reached Oak Ridge alive.

Under the direction of Jacob Furth, the returned survivors were housed in an isolated mouse room in individual cages. An ophthalmologist, using a slit lamp, examines randomly selected samples of the animals at regular intervals. The appearance of the hair, the occurrence of grossly detectable tumors and other pertinent data are recorded. When a mouse dies, a complete autopsy is performed, and samples of all tissues are preserved for histological study. A progress report on this study, as of 20 November 1951, has been submitted, and is reproduced in its entirety.[1]

B.2 PROGRESS REPORT

1. The study of the chronic consequences of exposure to nuclear radiations of an atomic bomb proceeds with no complications. Now, approximately 7 months after the exposure, most of the deaths are due to leukemia. Death from intercurrent infections has been minimal since receipt of the animals.

A slight mortality soon after receipt of the mice, occurring mainly among those receiving higher doses, has already been reported. The early lethality from exposure evidently does not end in 30 days, but there is quite a carry-over, terminating in the present series during the 6th or 7th week, when the weekly mortality declined to about one per week or 0.03 per cent of the population.

2. Leukemia began to appear during the 4th month after exposure and is now in its ascendancy. Table B.1 indicates a definite relation between leukemia incidence and intensity of exposure, the greatest incidence being among mice exposed to doses higher than the LD_{50}. Not a single case of leukemia has been observed among the 276 survivors exposed to neutrons.

Tumors occurred in the mammary gland region in many exposed mice. The incidence is given in Table B.1. This was unexpected

[1] The report was prepared by A. C. Upton, MD, K. W. Christenberry, MD, J. Moshman, and Jacob Furth, MD, all of the Biology Division, Oak Ridge National Laboratory. Dr. Furth is the project officer.

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TABLE B.1 INCIDENCE OF LEUKEMIA AND TUMORS IN SURVIVING MICE TO 19 NOVEMBER 1951

STATION NO.	NUMBER EXPOSED	LIVING 1 AUGUST 1951		DEAD OF LEUKEMIA		DEAD OF TUMORS	
		Number	Per Cent[a]	Number	Per Cent[b]	Number	Per Cent[b]
Easy Shot							
70k	220	1	0.4	0	0	0	0
l	220	0	0	0	0	0	0
m	220	5	2.3	0	0	0	0
n	220	15	6.8	0	0	0	0
o	220	39	17.8	0	0	1	2.6
p	220	72	32.7	6	8.3	0	0
q	220	92	41.8	4	4.3	0	0
r	220	140	63.6	1	0.7	0	0
s	220	167	75.9	3	1.8	0	0
t	220	191	86.8	3	1.6	0	0
u	220	204	92.7	7	3.4	1	0.5
v	220	208	94.5	5	2.4	1	0.5
w	220	208	94.5	1	0.5	0	0
71a	220	43	19.5	0	0	0	0
b	220	150	68.2	1	0.6	3	2.0
c	220	212	96.3	0	0	1	0.5
d	220	215	97.7	2	0.9	1	0.5
e	220	213	96.8	1	0.5	1	0.5
85d[c]	50	44	88.0	0	0	0	0
e	50	46	92.0	0	0	2	4.3
f	50	50	100	0	0	0	0
George Shot							
85b	30	26	86.6	1	3.3	3	10.0
c	30	28	93.3	0	0	1	3.6
d	20	18	90.0	0	0	0	0
e	30	30	100	0	0	1	3.3
f	30	27	90.0	0	0	0	0
Controls[d]	620	611	98.5	0	0	0	0

[a] Per cent of those exposed.
[b] Per cent of those living 1 August 1951.
[c] Mice in the 85 series stations were shielded by 7 in. of lead and received only neutrons.
[d] Healthy unexposed LAf_1 mice from Eniwetok.

since, according to Egon Lorenz, mammary tumors occur late in life of mice of this strain exposed to gamma rays and cutaneous tumors are very rare. Since the occurrence of such tumors is five times as frequent in the mice exposed to neutrons, the question is whether these tumors could be caused by nuclear reactions of neutrons with some element present in the accessory glands of the skin or in the mammary ducts. Other types of tumor are not apparent thus far.

3. Opacities of the lens began to make their appearance about 70 days after exposure, and now all exposed animals have some opacities. This is well explained by our earlier observation that the threshold dose of X rays inducing opacities of the lens is somewhere between 30 and 15 r. The progress of cataracts among the animals exposed is indicated in Table B.2. There is a distinct preferential neutron effect as concerns cataract induction.

4. Graying of the hair occurred in animals in definite relation to the intensity of the exposure, as one might expect from data in the literature. A summary of observations is given in Table B.3.

[redacted]

[redacted]

TABLE B.2 INCIDENCE OF OPACITIES IN THE LENS, SLIT LAMP EXAMINATION

MONTH	JUNE 1951			SEPTEMBER 1951				NOVEMBER 1951			
Degree of Opacity	0	+	++	0	+	++	+++	0	+	++	+++
Easy Shot Station											
70k					1						
m	4				1	4					
n					1	3				2	1
o						5					
p	11										
q	12				1	2				3	
r	24				2	1					
s	23	1			4	3					
t	29									3	
u						3					
v					2	1					
w					6					3	
71a											
b											
c					2				3		
d					7						
e					9						
85d[a]	21				1	4	1			1	2
e	28	9			3						
f					6						
George Shot Station											
85b	14									3	
c	28				3						
d	14	2			2						
e					6				3		
f					3						
Control	68			27				3			

[a] Mice in series 85 stations received only neutrons.

5. The X-ray controls have been received only recently from LT V. P. Bond, NRDL. These mice were raised there, using stock obtained from Eniwetok. They are not perfect controls but should serve for tentative orientation as to the relative efficiency of neutrons, gamma rays, and X rays in producing graying, cataracts, leukemia, and tumors.

6. It is premature to draw final conclusions, but the following general considerations are submitted:

(a) Atomic bomb explosions can be utilized for basic scientific and applied studies which are superior in many respects to the laboratory experiments performed thus far. For example, certain major factors are ideally identical and uniform, such as the source of the exposure, the period of observation, and other variables related to time and space. Neutron exposure of mammals on a large scale is barely feasible otherwise.

(b) The present large-scale study need not be duplicated. It seems adequate as a base line to enable the planning of several much smaller projects, well conceived and executed on a statistically significant scale.

[redacted]

[redacted]

TABLE B.3 EXTENT OF DEPIGMENTATION OF FUR[a]

DATE	25 JULY 1951						1 OCTOBER 1951						15 NOVEMBER 1951					
Anatomical Region	Head	Neck	Shoulders	Abdomen	Dorsum	Sacral Region	Head	Neck	Shoulders	Abdomen	Dorsum	Sacral Region	Head	Neck	Shoulders	Abdomen	Dorsum	Sacral Region
Easy Shot Station																		
70k	20	20	10	10	10	0							40	30	30	30	20	0
m	20	20	20	10	10	0	35	35	27	23	18	15	40	40	40	35	28	13
n	25	23	16	12	10	7	27	27	22	18	15	12	39	36	28	26	16	20
o	24	20	16	13	10	3	34	27	24	24	19	14	40	40	35	36	24	20
p	24	25	14	11	4	1	31	26	24	22	13	9	40	37	32	31	24	18
q	22	21	17	13	9	3	27	26	23	21	14	9	39	39	34	33	20	13
r	20	20	15	12	8	2	27	27	26	22	13	9	40	36	30	32	22	14
s	19	18	15	12	14	5	28	24	18	16	9	4	39	35	32	28	22	20
t	17	18	10	10	9	3	28	24	22	21	16	9	38	35	31	30	21	14
u	22	21	12	11	10	4	28	23	20	17	14	7	37	33	26	25	15	10
v	18	17	8	8	8	3	19	18	18	18	6	4	31	24	21	21	15	9
w	12	12	9	9	9	3	16	14	12	13	8	4	16	14	11	15	11	4
71a	8	8	7	7	6	2	12	13	11	14	10	4	17	10	7	16	10	8
b	4	5	4	5	3	0	2	4	2	4	1	1	8	8	7	9	6	3
c	2	3	3	3	0	0	2	2	0	3	0	0	1	1	0	2	1	0
d	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
e	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
85d	17	17	13	12	2	0	11	12	10	11	9	4	22	18	16	14	12	8
e	5	6	6	6	4	0	2	3	1	4	0	0	4	3	2	4	1	1
f	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
George Shot Station																		
85b	8	10	10	10	10	2	7	7	4	8	4	3	13	16	14	17	13	10
c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
f	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[a] 0 = no depigmentation, normal brown color, 10 = hair faintly gray; 20 = hair gray; 30 = hair gray white, 40 = hair white. The figures given are average values calculated from observation of 10 to 30 mice per station, except 70k, where only one was available.

[redacted]

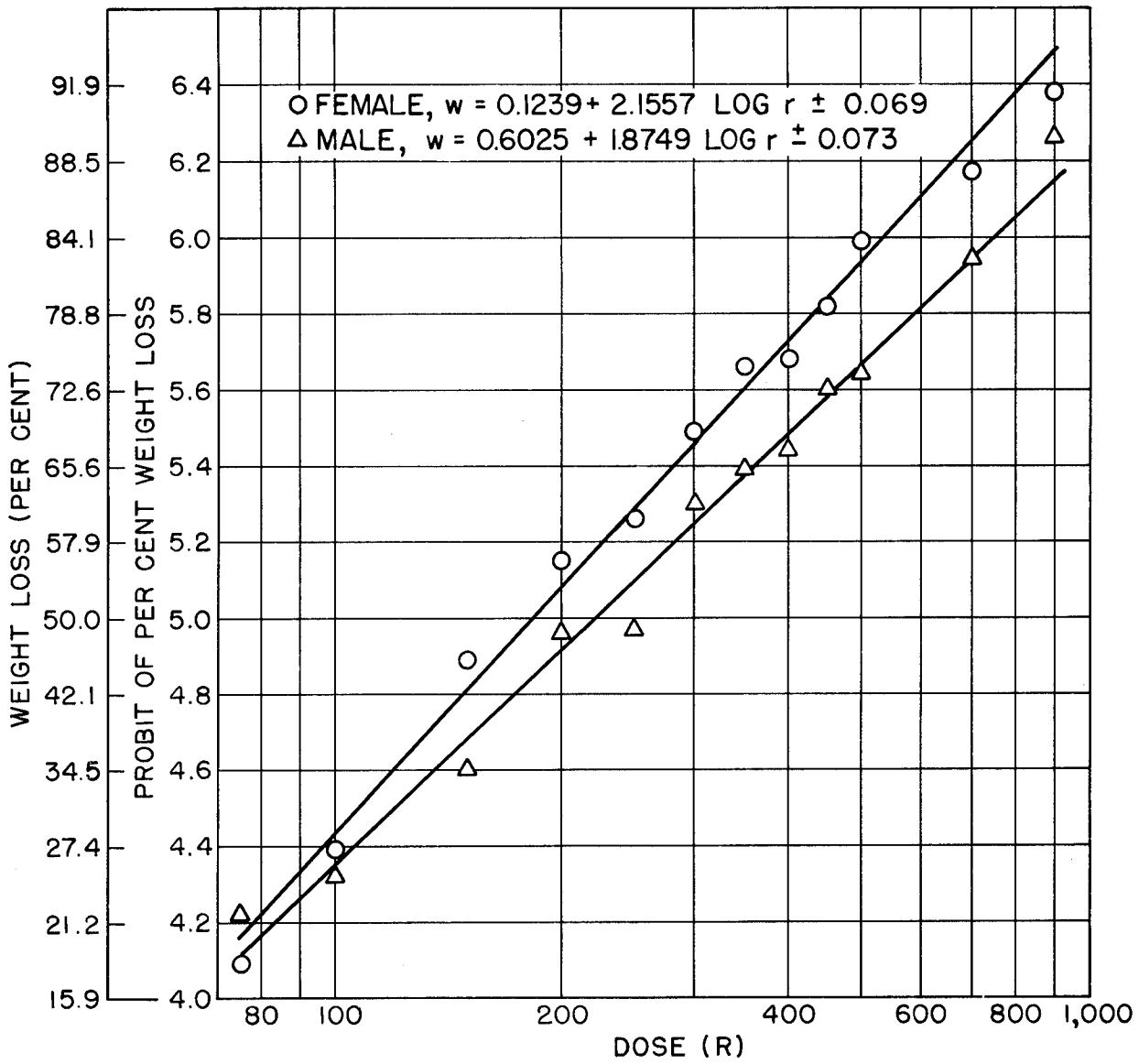


FIG. 3.1 Effect of 230-KVP X Radiation on the Weight of the Thymus of the LAf_1 Mouse. (*Greenhouse Report, Annex 2.2, Part I.*)

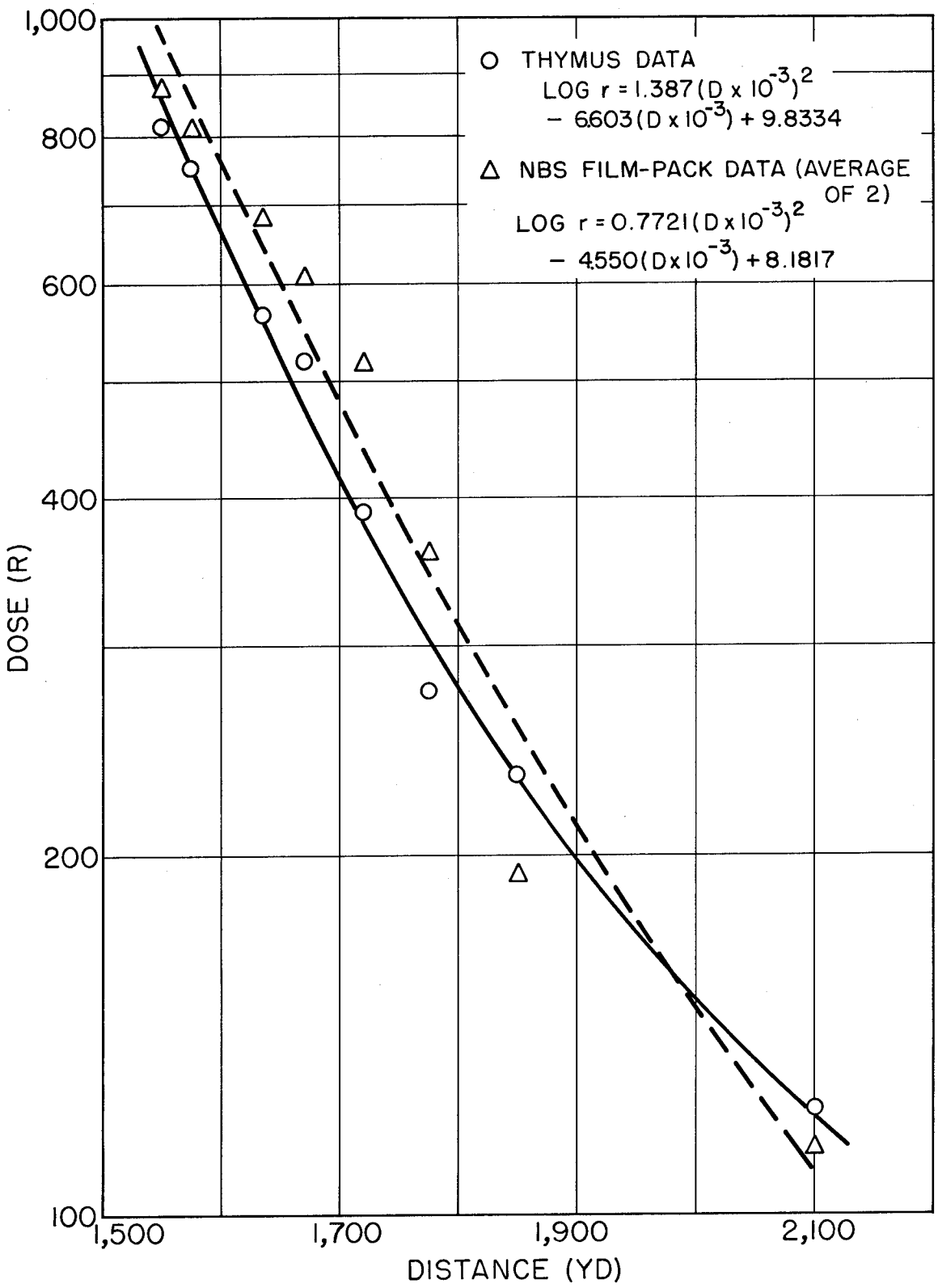


FIG. 3.2 Biological Effectiveness of Bomb Gamma Radiation in Terms of Equivalent Roentgens of 230-KVP X Rays as a Function of Distance from Ground Zero, Dog Shot. The NBS film was calibrated with 600-KVP X rays. (*Greenhouse Report, Annex 2.4, Part I, Sec. 1.*)

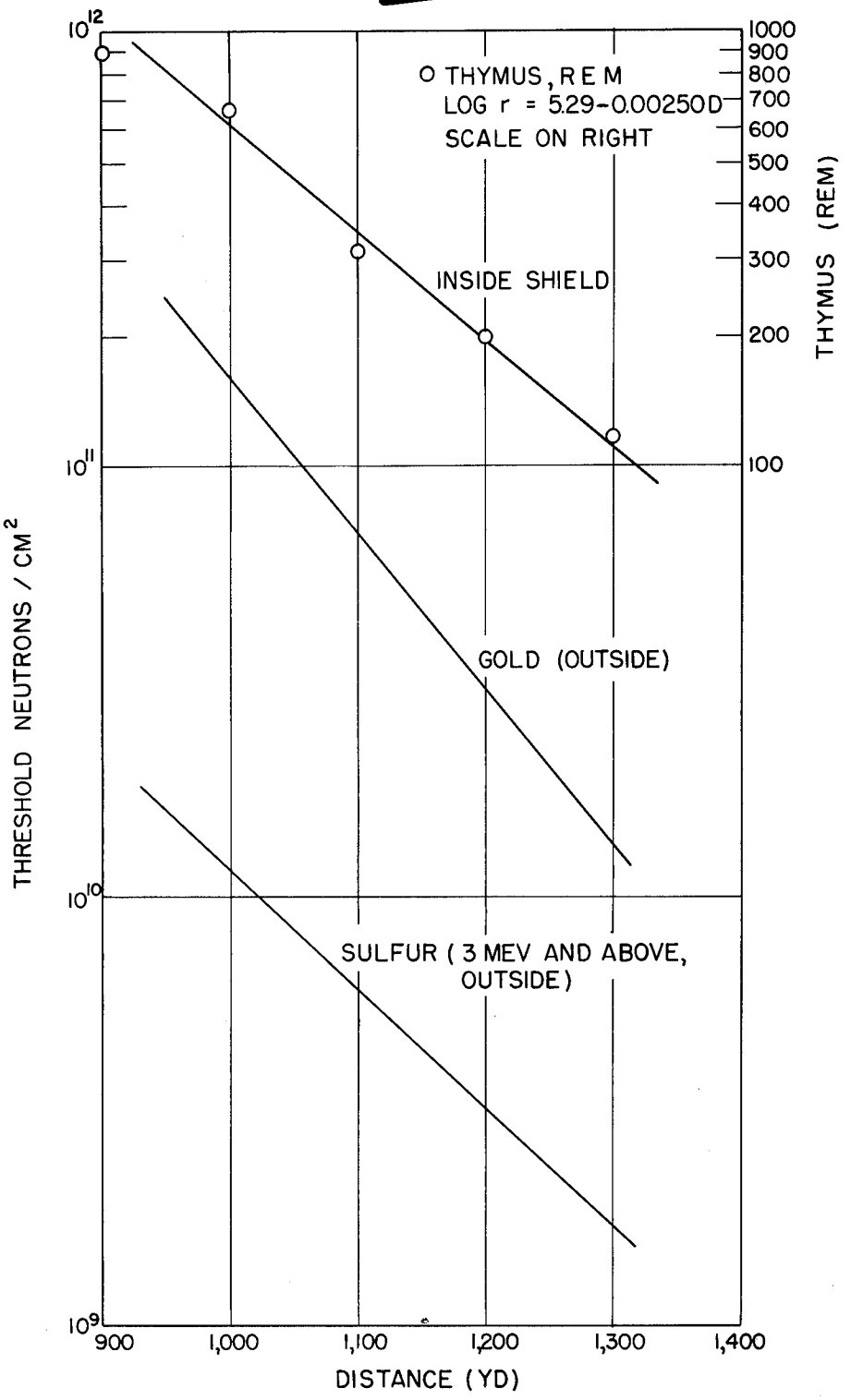


FIG. 3.3 Biological Effectiveness of Bomb Neutrons inside the 7-in.-thick Lead Hemispheres, Expressed in Roentgens Equivalent of 230-KVP X Rays, as a Function cf Distance from Ground Zero, Dog Shot. The values for threshold neutrons were obtained outside the shield. The scale for thymus roentgens equivalent man is located arbitrarily and implies no relation to the neutron scale. (*Greenhouse Report, Annex 2.4, Part I, Sec. 2.*)

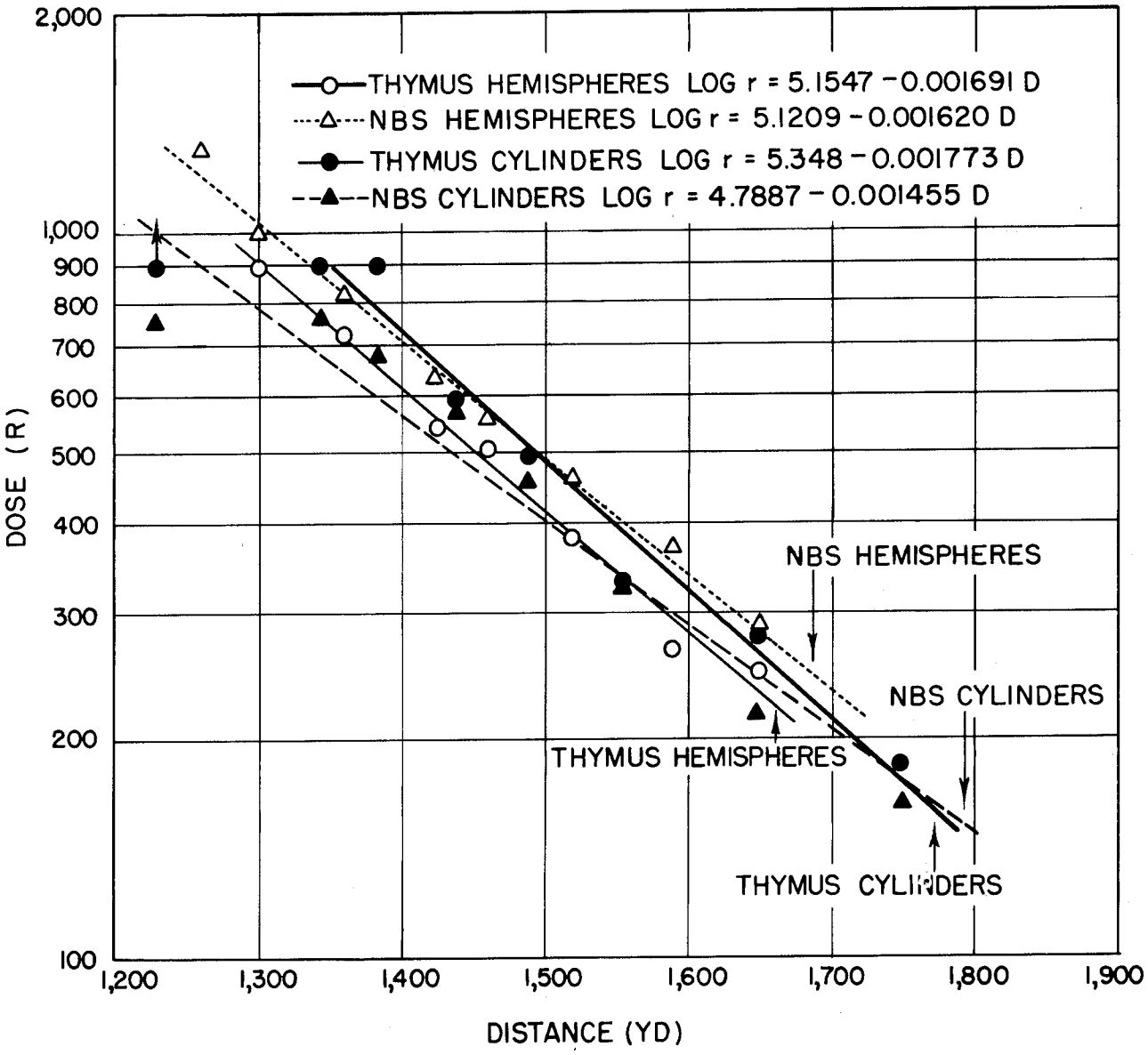


FIG. 3.4 Biological Effectiveness of Bomb Gamma Radiation in Terms of Equivalent Roentgens of 230-KVP X Rays, Measured inside the Hemispheres (open circles) and the Cylinders (closed circles) as a Function of Distance from Ground Zero, Easy Shot. Film-pack readings are represented by triangles. (*Greenhouse Report, Annex 2.4, Part I, Sec. 1.*)

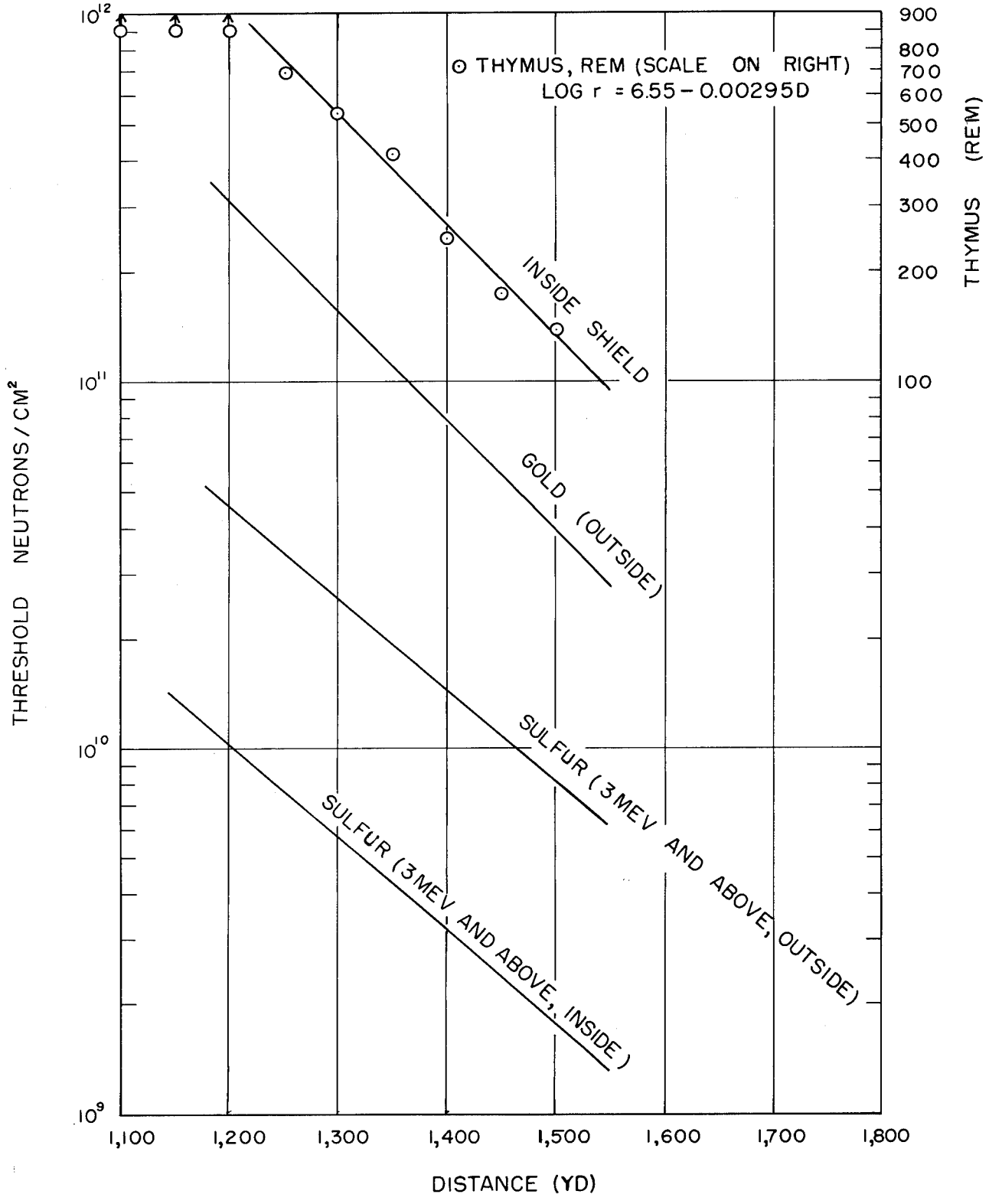


FIG. 3.5 Biological Effectiveness of Bomb Neutrons inside the 7-in.-thick Lead Hemispheres, Expressed in Roentgens Equivalent of 230-KVP X Rays, as a Function of Distance from Ground Zero, George Shot. The scale for thymus roentgens equivalent man is located arbitrarily and implies no relation to the neutron scale. (*Greenhouse Report, Annex 2.4, Part I, Sec. 2.*)

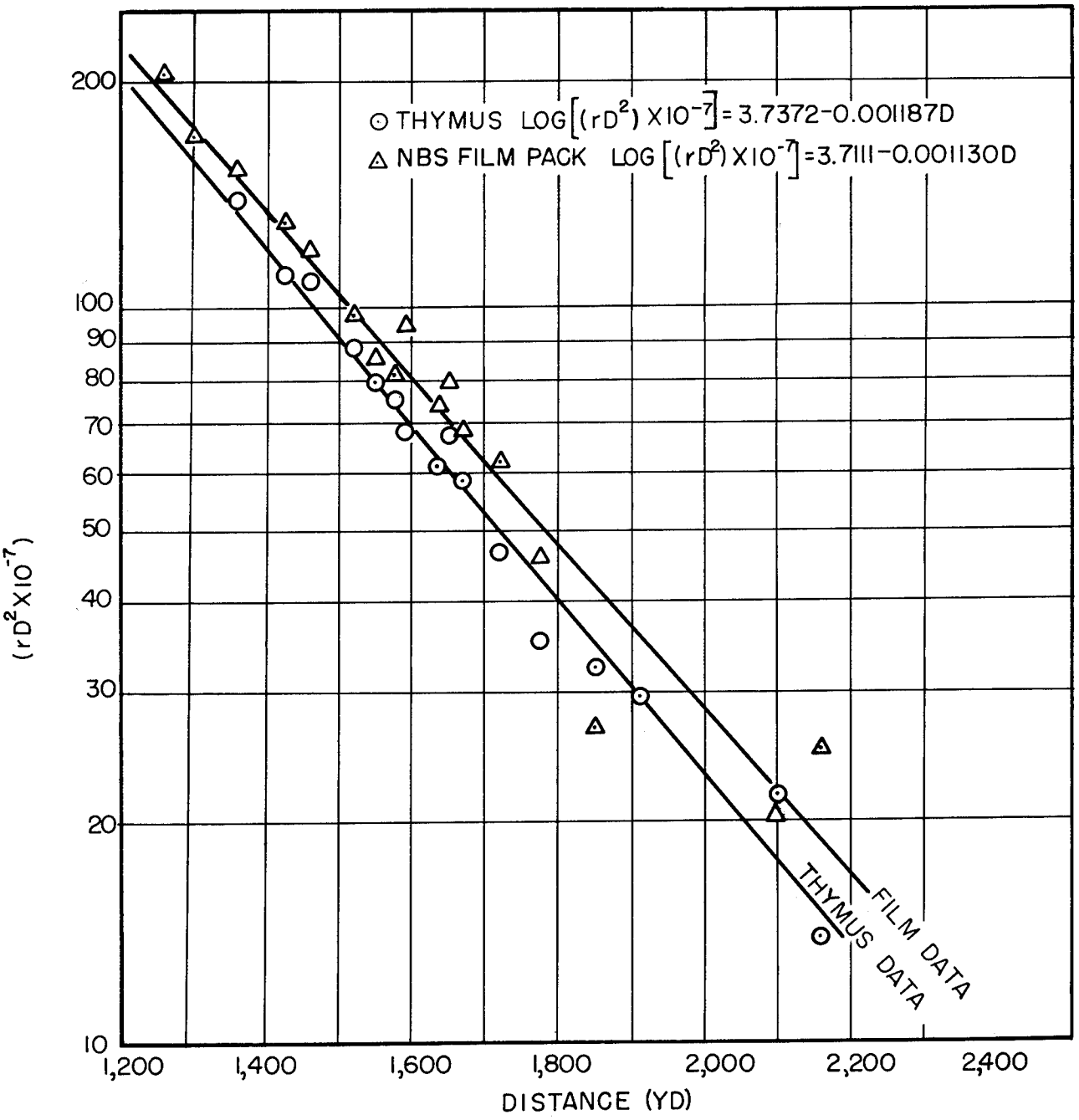


FIG. 3.6 Composite Curves of Biological Effectiveness of Bomb Gamma Radiation (expressed in roentgens equivalent of 230-KVP X rays) and NBS Film-pack Readings (calibrated with 600-KVP X rays) at Varying Distances from Ground Zero. The data from Dog, Easy, and George Shots have been combined and normalized to the yield of Easy Shot. (*Greenhouse Report, Annex 2.4, Part I, Sec. 1.*)

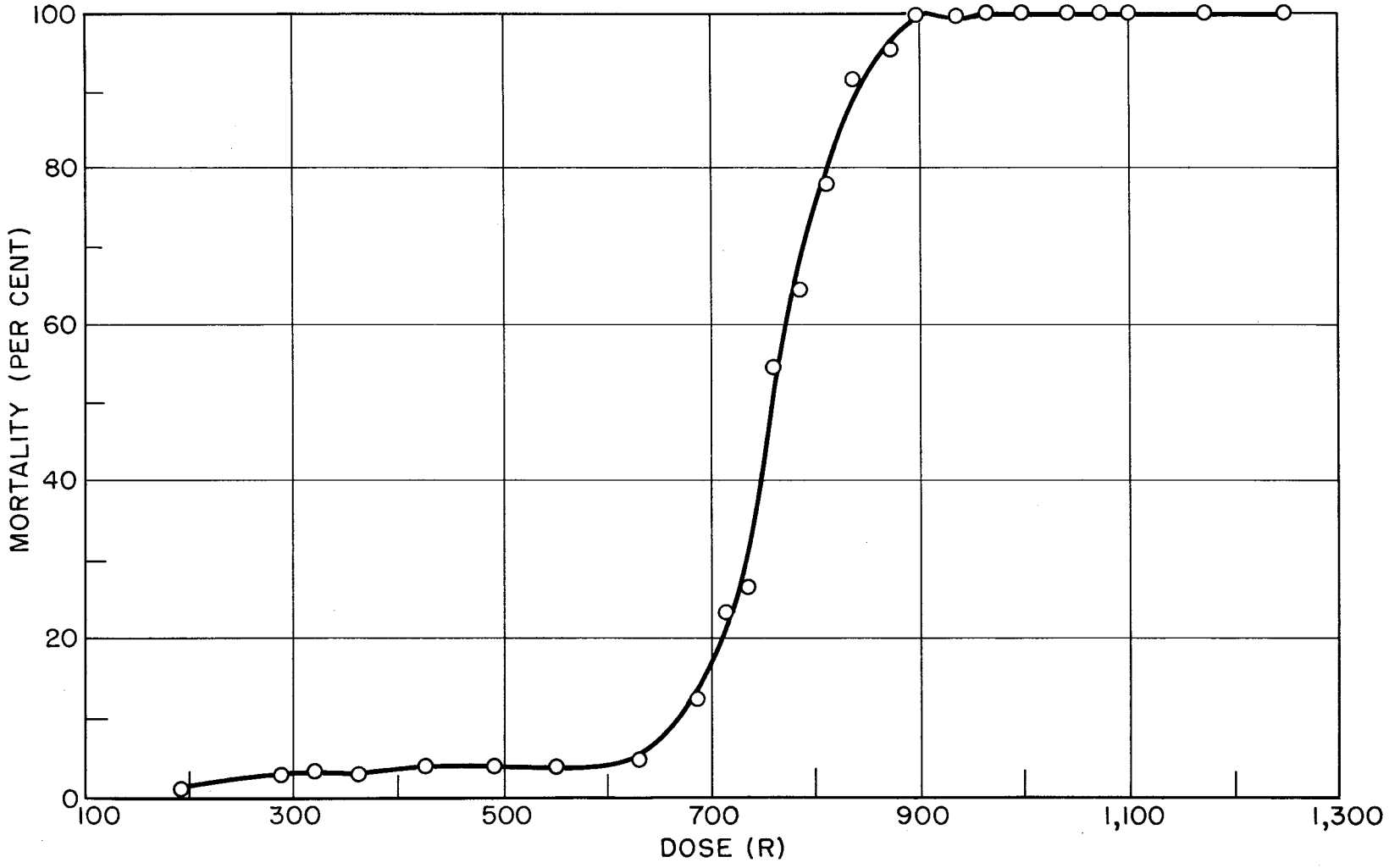


FIG. 3.7 Twenty-eight Day Mortality of LAf_1 Mice as a Function of Dose of Bomb Gamma Radiation, Easy Shot. (*Greenhouse Report Annex 2.5, Part I.*)

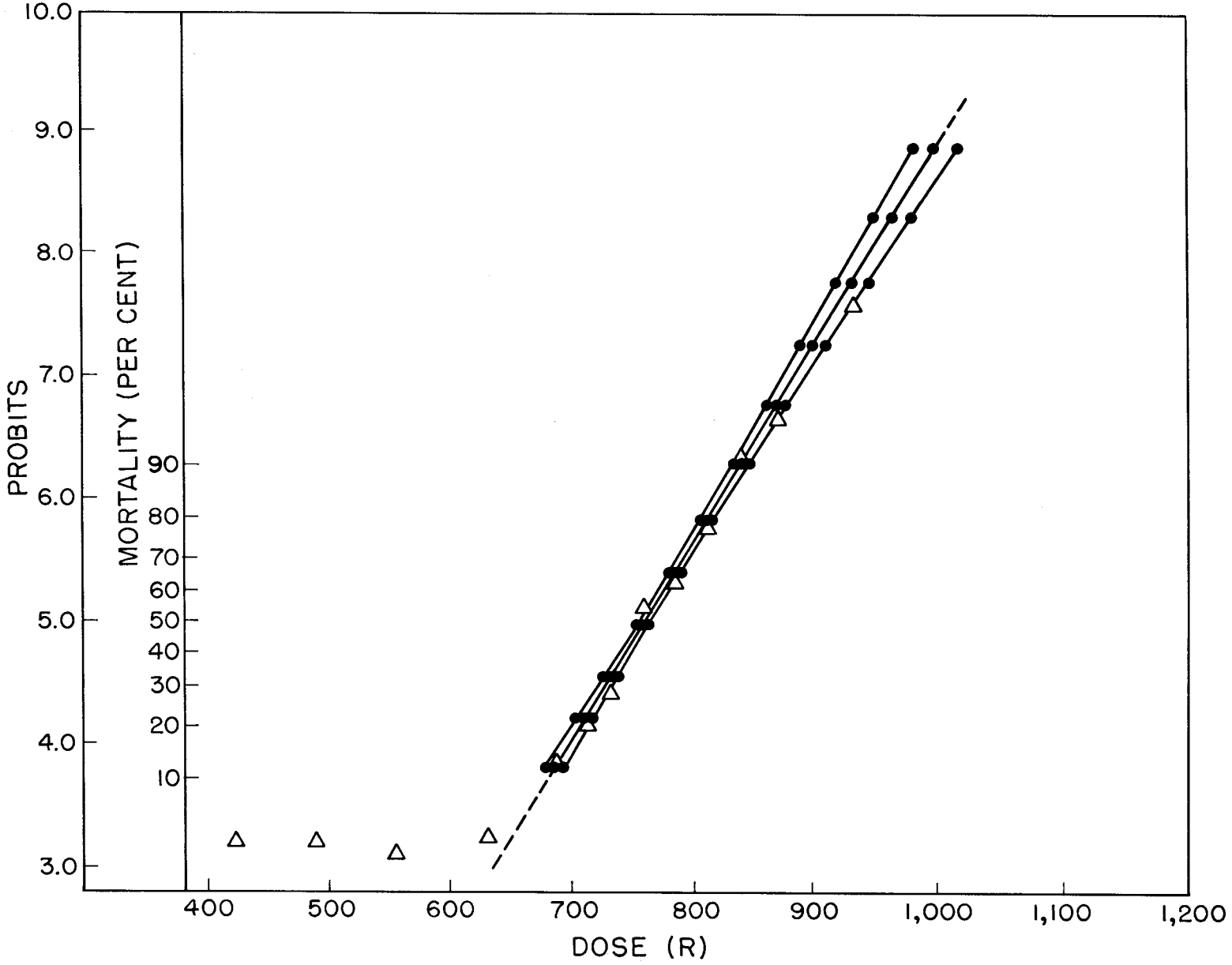


FIG. 3.8 Probit Transformation of Curve of 28-day Mortality as a Function of Dose of Bomb Gamma Radiation for LAf_1 Mice, Easy Shot. (*Greenhouse Report, Annex 2.5, Part I.*)

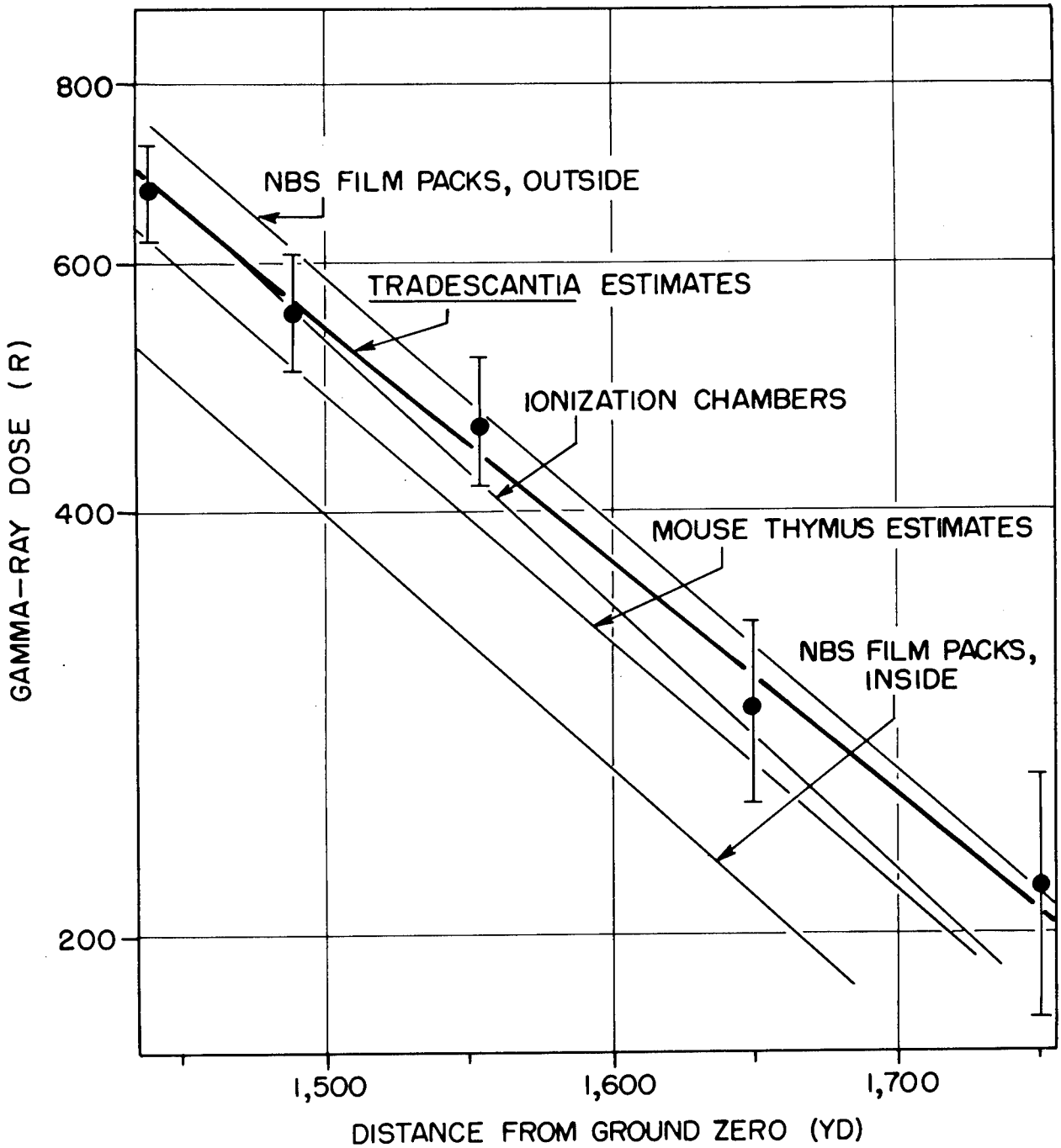


FIG. 3.9 Estimates of Bomb Gamma-ray Dose as a Function of Distance Using *Tradescantia,* Easy Shot. The *Tradescantia,* NBS film packs, and mice were inside cylinders of the 70, 71 series. The ionization chambers were in lucite spheres. (*Greenhouse Report, Annex 2.4, Part III.*)

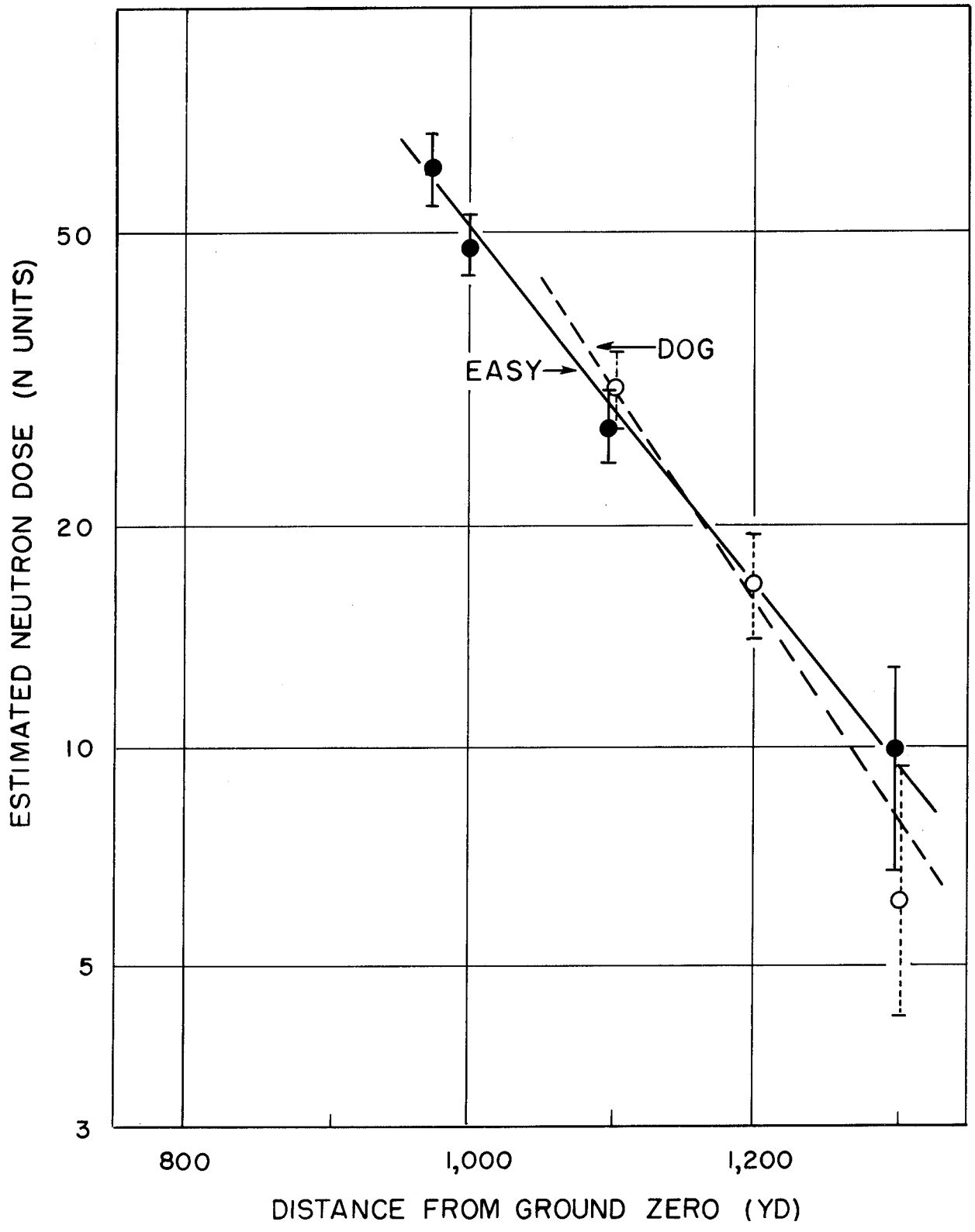


FIG. 3.10 Estimates of Neutron Dose, in n Units, as a Function of Distance, Using *Tradescantia*, Dog and Easy Shots. (*Greenhouse Report, Annex 2.4, Part III.*)

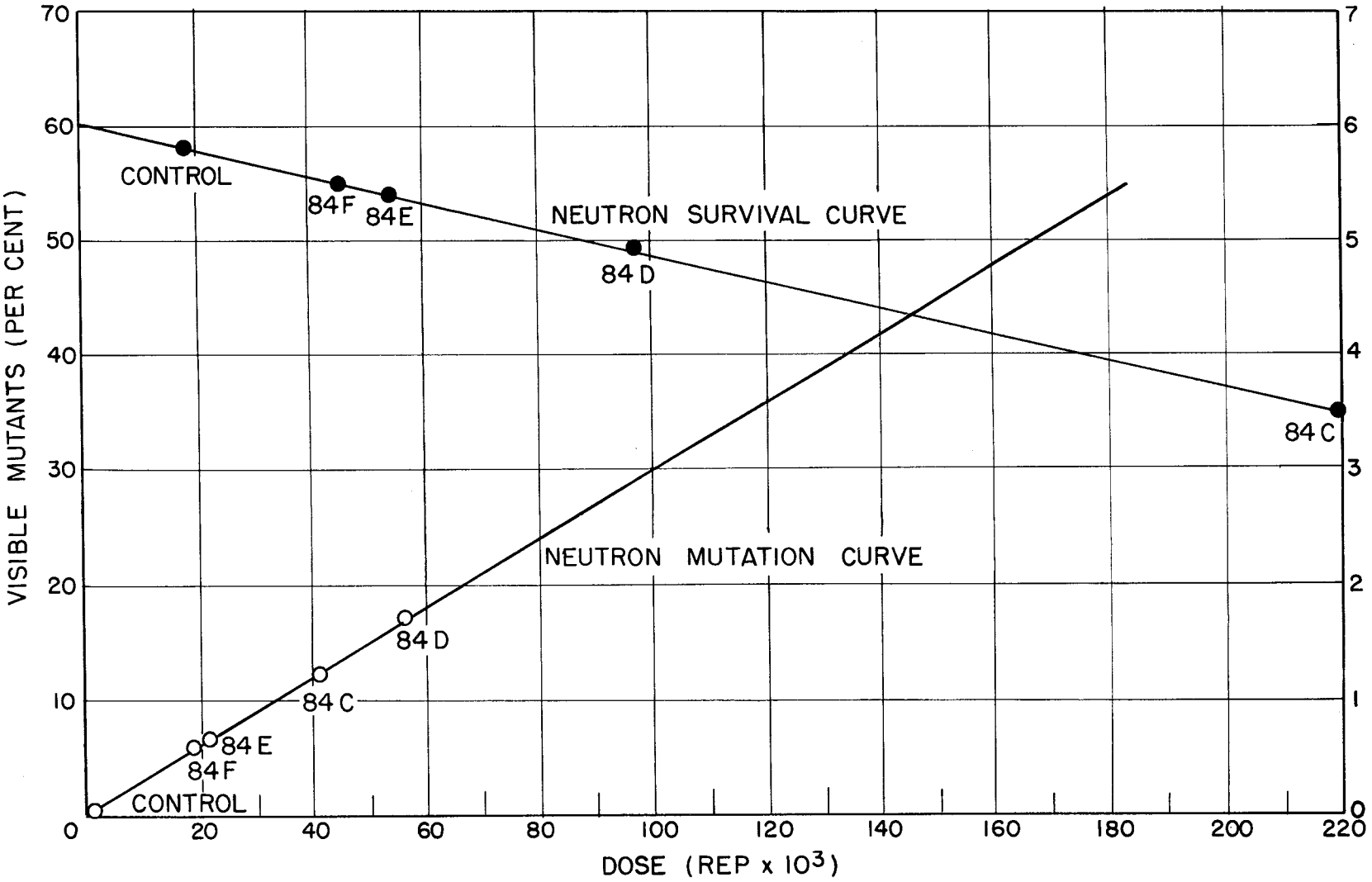


FIG. 3.11 Mutation and Survival Rate of *Glomerella* as Functions of Dose of Radiation. The curves were obtained from fast neutrons from the reactor at Oak Ridge. The points on the curves were obtained in the 84 series stations at Easy Shot. (*Greenhouse Report, Annex 2.10.*)

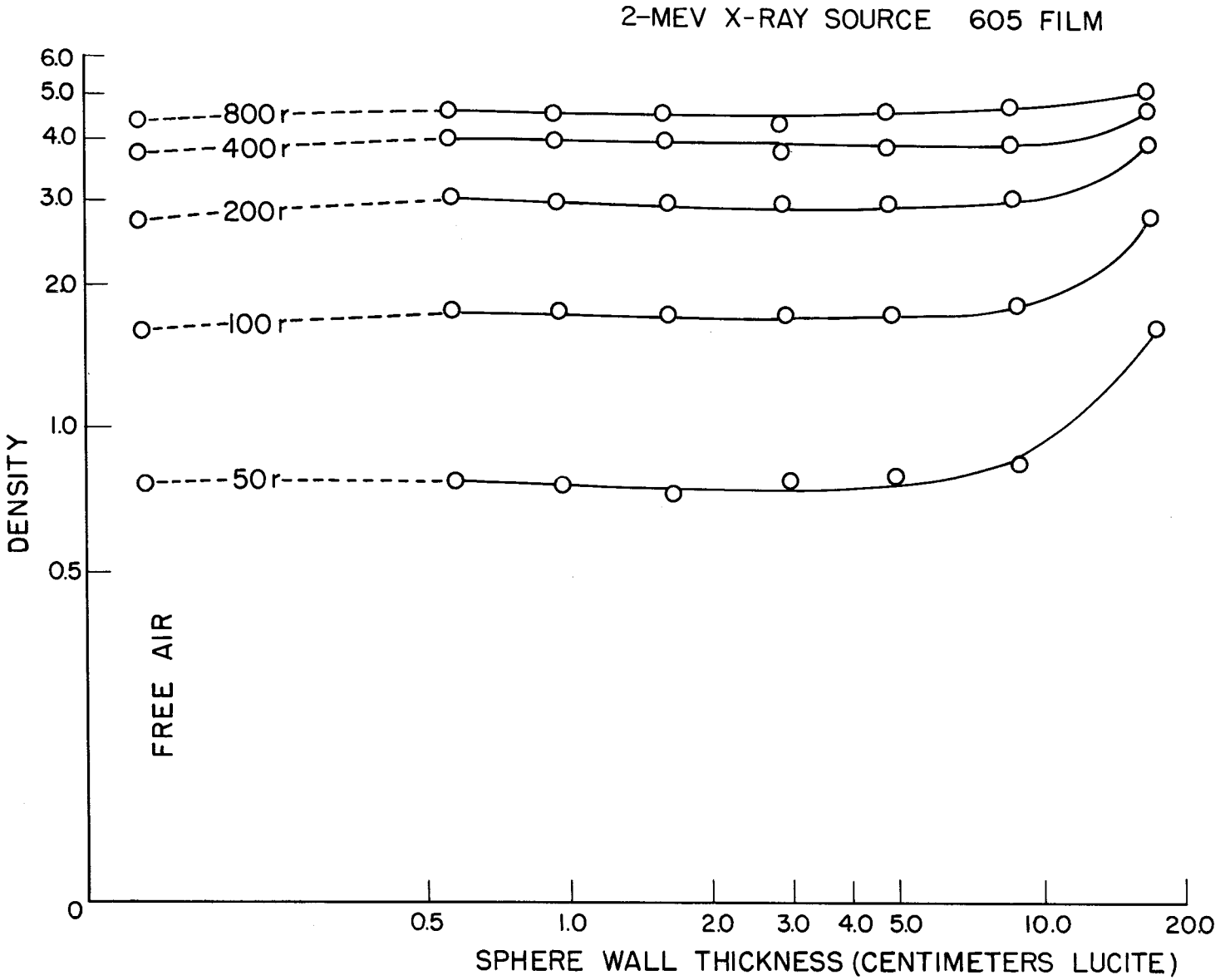


FIG. 4.1 Density Readings of No. 605 Film Exposed to 2,000-KVP X Rays inside Lucite Spherical Phantoms, the Wall Thicknesses of Which Varied from 0.5 to 17.5 cm. (*Greenhouse Report, Annex 2.4, Part II.*)

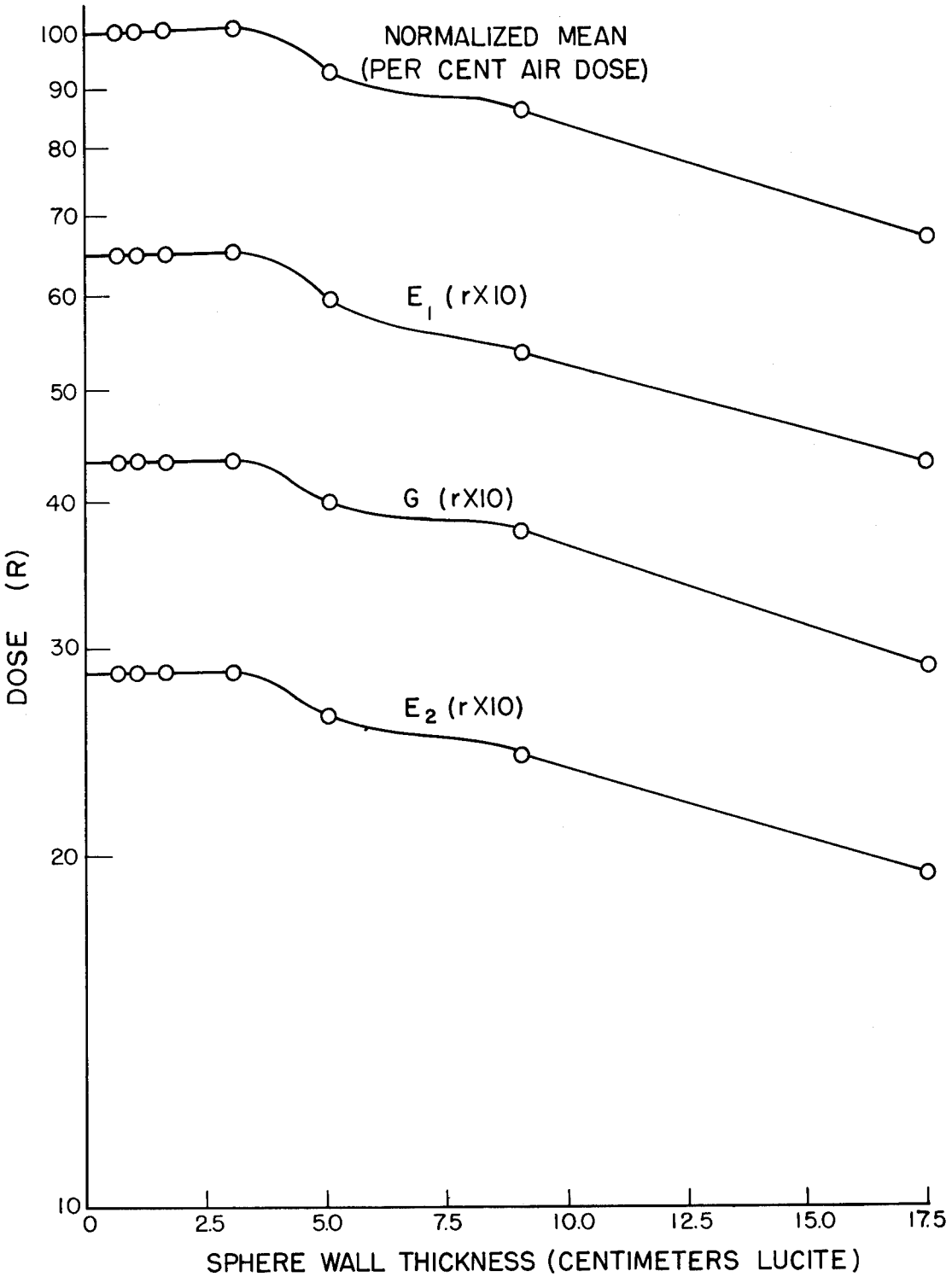


FIG. 4.2 Absorption of Bomb Gamma Radiation in Lucite Spherical Phantoms, Easy and George Shots. The dose was measured with Sievert ionization chambers. The top curve is a composite of the three lower ones, with the points normalized to per cent air dose. The readings in spheres with wall thickness 0.5 to 2.5 cm were taken as equal to the air dose. (*Greenhouse Report, Annex 2.4, Part II.*)

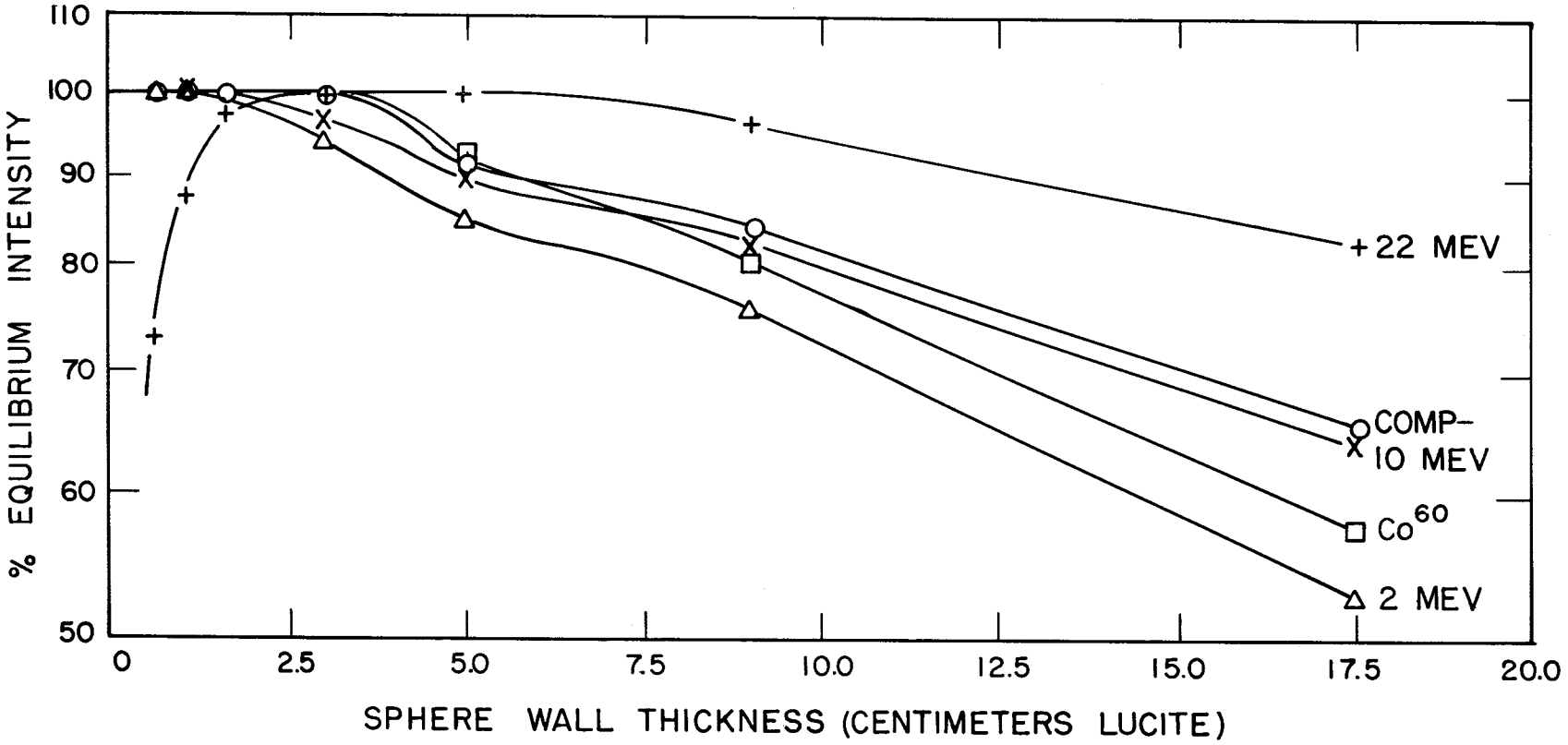


FIG. 4.3 Absorption of Radiation from Various Sources in Lucite Spherical Phantoms. The curve labeled "Comp" is the top curve of FIG. 4.2, and represents the quality of the bomb gamma radiation. The curve labeled "10 Mev" was obtained with the NBS betatron. (*Greenhouse Report, Annex 2.4, Part II.*)

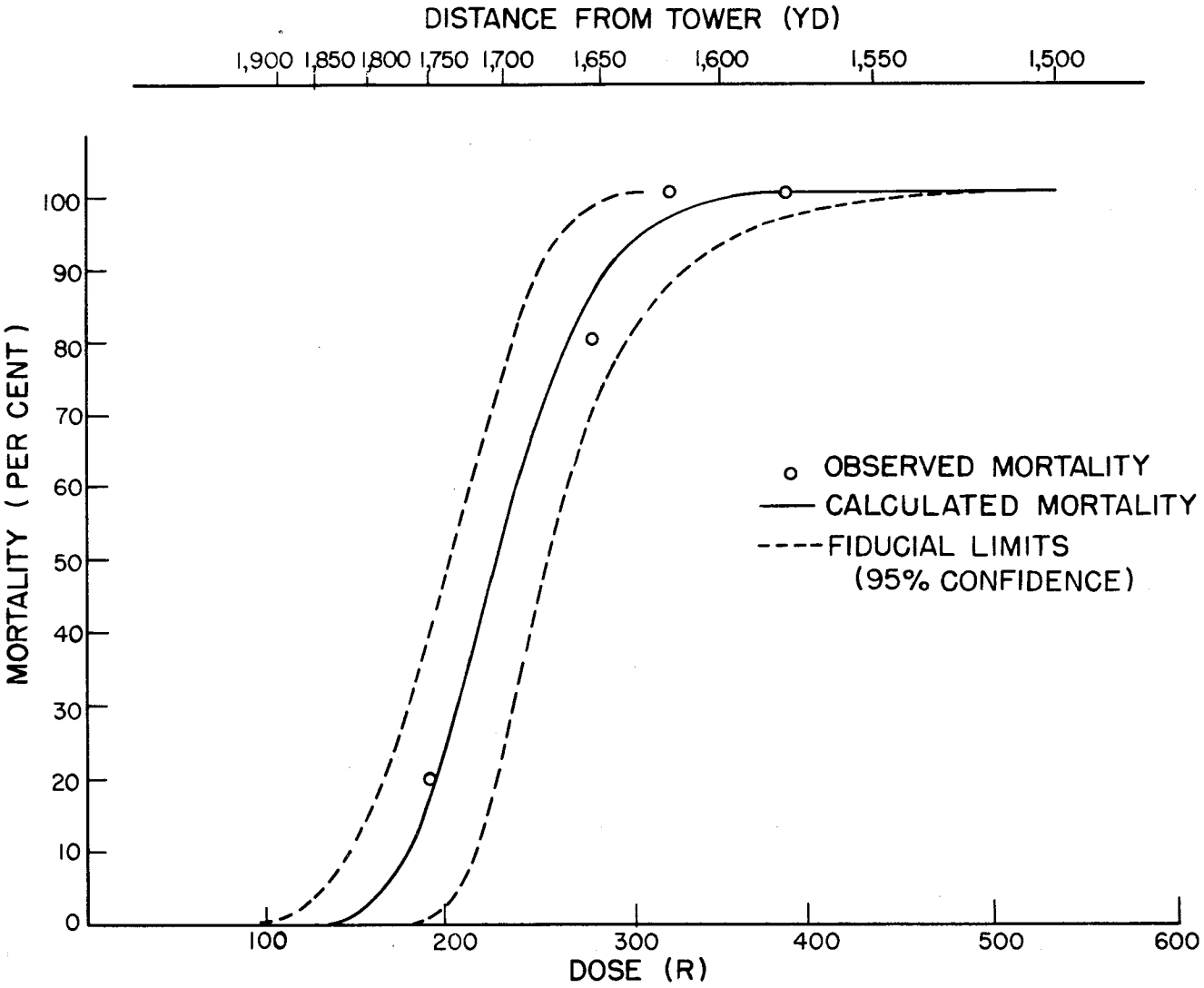


FIG. 5.1 Thirty-day Dose-Mortality Curve for Swine Exposed to Gamma Radiation at Easy Shot. The values for dose (r) were obtained with Sievert ionization chambers. (*Greenhouse Report, Annex 2.5, Part II.*)

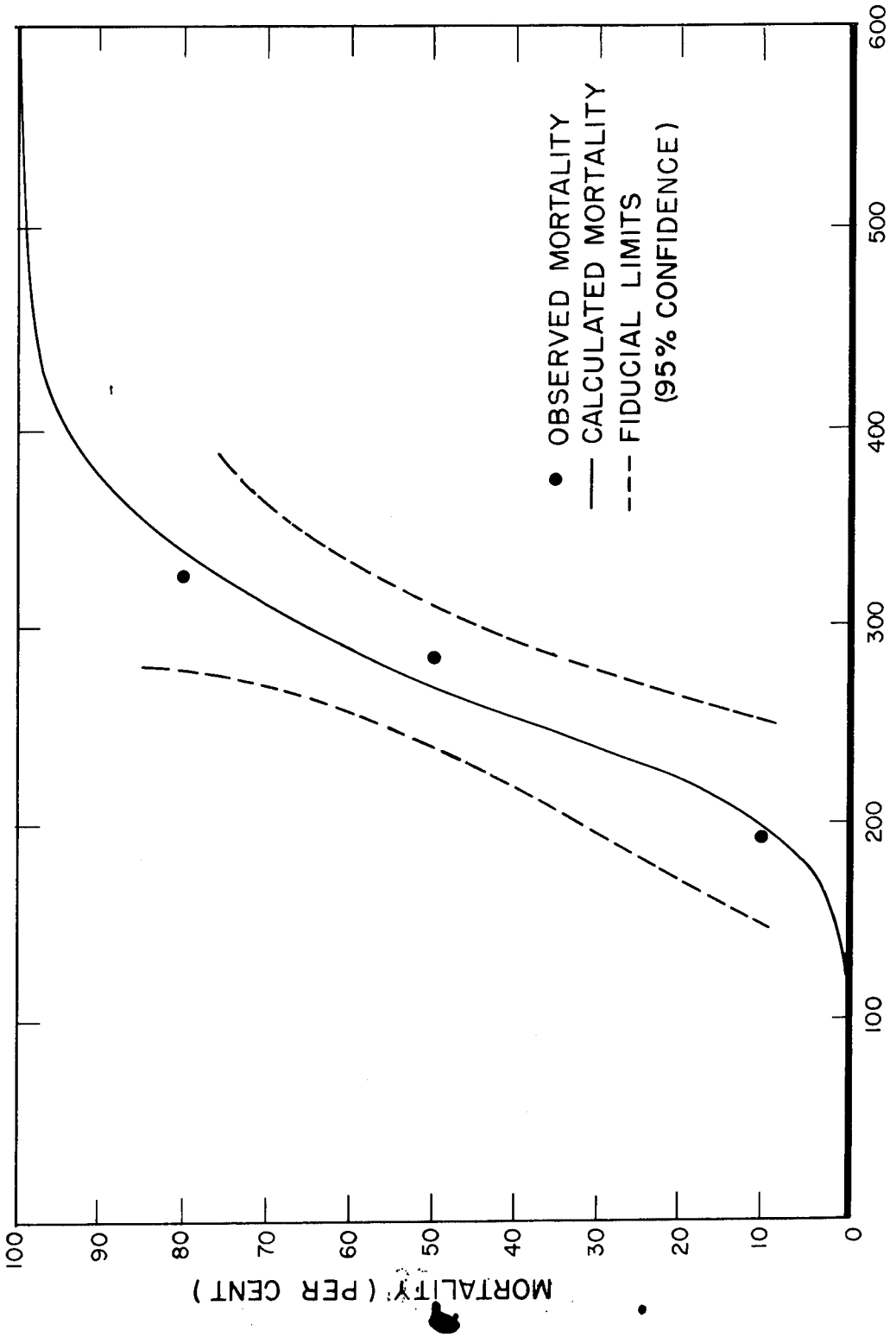


FIG. 5.2 Thirty-day Dose-Mortality Curve for Dogs Exposed to Gamma Radiation at Easy Shot. (*Greenhouse Report, Annex 2.5, Part III.*)

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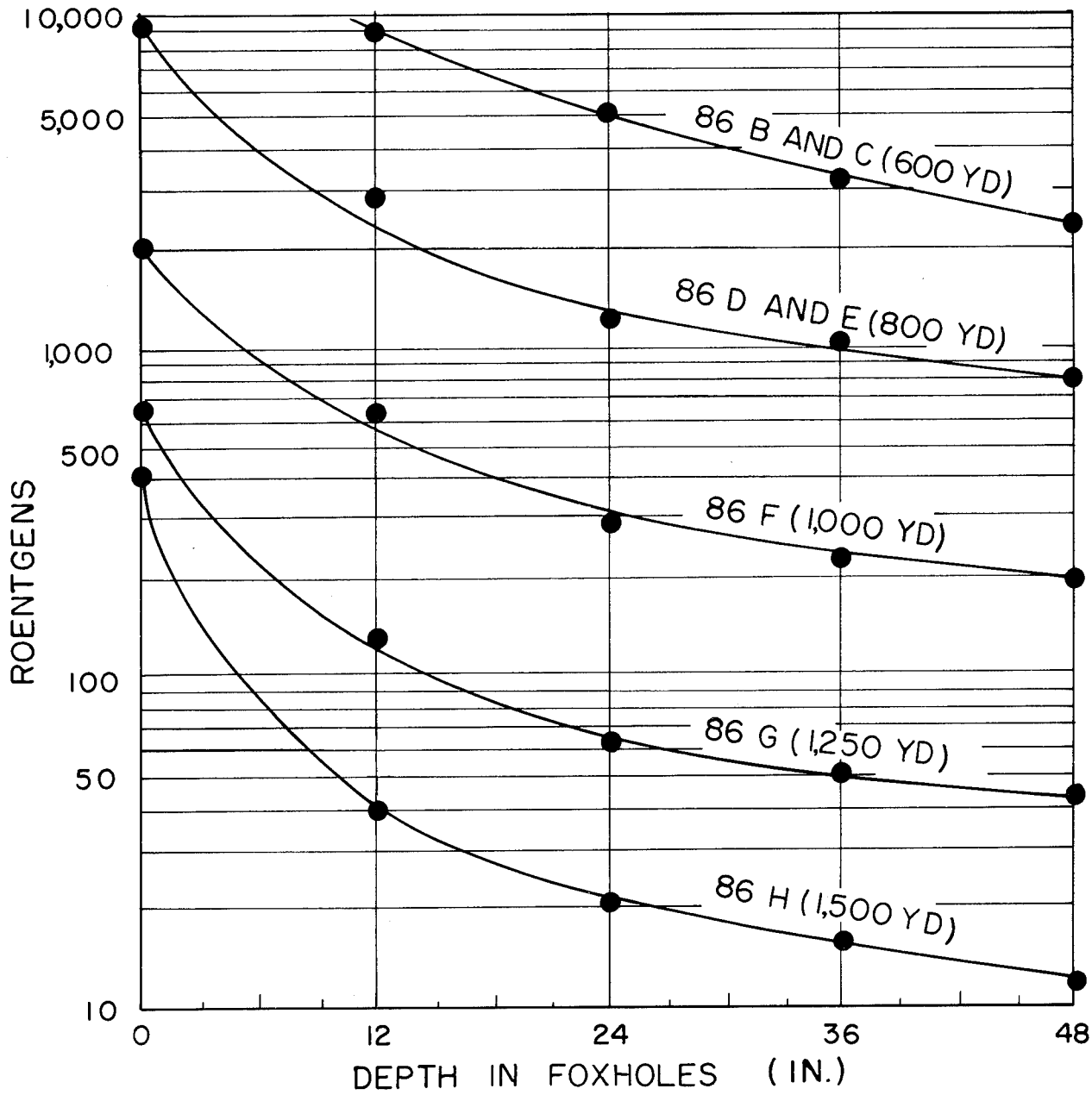


FIG. 9.1 Variation of Bomb Gamma Radiation with Depth in Foxholes at Various Distances from Item Zero. The estimates of dose were made with NBS film packs placed against the protected wall of the foxhole. (*Greenhouse Report, Annex 2.9.*)

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